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**IMPROVED MODELS OF THE INNER AND OUTER RADIATION BELTS**

K. A. Pfitzer

McDonnell Douglas Space Systems Corp  
5301 Bolsa Avenue  
Huntington Beach, CA 92647

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AIR FORCE SYSTEMS COMMAND  
HANSCOM AIR FORCE BASE, MASSACHUSETTES 01731-5000

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KEVIN J. KERNS  
Contract Manager



E.G. MULLEN  
Branch Chief



RITA C. SAGALYN  
Division Director

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## 1.0 Introduction

Considerable progress has been made in the understanding of magnetospheric processes in the last 25 years. During this time much of the effort has been focused on understanding processes operating in the tail of the magnetosphere and near the magnetospheric boundaries. The inner magnetosphere has not been extensively investigated in the last 10 to 20 years. The Combined Release and Radiation Effects Satellite (CRRES) Program is designed to make a substantial contribution to understanding this region of space.

In this effort McDonnell Douglas Space Systems Company (MDSSC) will introduce novel new modelling approaches and will satisfy one of main goals of the CRRES mission, the development of new static and dynamic radiation belt models. Such models are an important tool for engineers for the design of systems that can survive in the space environment. The present radiation belt models that are now used by both the scientific and engineering communities are the Vette radiation models developed by the National Space Sciences Data Center (NSSDC) in the late 1960's and early 70's. The data sets which were used to develop the Vette models were acquired by instruments that are quite primitive compared to today's state-of-the-art instruments. Nevertheless these older models have served the community well.

The present NSSDC developed models are organized in B, L space, a coordinate system developed by C. E. McIlwain in 1961. This coordinate system has been virtually unchanged since that time. Improvements have come only in the form of improved computational techniques. Although the B, L system has proven useful in the inner zone, its use in the outer zone has not been as successful.

This CRRES analysis effort will include the development of new tools for the organization of the data. This effort will develop novel new techniques for organizing charged particle data in the inner and outer zone. In the inner zone we will develop a model that not only takes into account the effect of the magnetic field in organizing the charged particles but also the effect of the solar cycle dependent atmosphere in shaping the low altitude region of the inner radiation belt. In the outer zone we will provide a coordinate system that can correctly represents adiabatic changes in the radiation belt and fully takes into account drift shell splitting and yet represents the entire outer zone in terms of only two parameters, the first and second invariant for each observation and pitch angle. Once the new tools developed under this effort are implemented and a best fit is made to the CRRES data, a high quality radiation belt model will be created that will be valid for all epoch within a solar cycle and for all magnetic conditions of the magnetosphere. In the inner zone, the new model will permit calculation of the fluxes during any part of the solar cycle. In the outer zone the model will help separate adiabatic changes from non adiabatic variations, allow the calculation of particle fluxes for all states of magnetospheric compression, and will help theorists explain many of the observed changes within the magnetosphere.

The analysis effort consists of two distinct phases, the first of these is the development of the required computer code for defining the new coordinate system and the second is the fitting of the data utilizing the new coordinate system. By its very nature the development of the computer code cannot be completely decoupled from the analysis of the data. The quality of the data and the various features found within the data stream will dictate the ultimate development of the model coordinate system and the final fit of the data.

## 2.0 A Pitch Angle Dependent Invariant Routine

During the first year of the contract almost all of the effort has been spent developing and polishing the various software tools that will be required to produce a new high precision CRRES model of the inner and outer zones. Some of this software must yet be verified using CRRES data. This technical report will describe the software that is considered fully operational and which is available for use by any of the CRRES investigators.

This annual report will concentrate on describing the software that could be verified without using the CRRES data. The major achievement during the first year was the development of a new B,L code that calculates the invariant at the satellite for many different pitch angle particles. Calculating B,L has always been a computationally expensive procedure and thus considerable effort was expended to produce a code that is *efficient and cost effective*. The calculation of the second invariant requires the calculation of a line integral that makes many calls to the magnetic field subroutine.

### 2.1 A Fast Version of IGRF

Present versions of B,L use only the internal model of the magnetic field. The CRRES code must use both internal and external models of the magnetic field, since it must take into account drift shell splitting in the outer magnetosphere. Thus one of the most important routines for saving computer time is the development of an internal and external magnetic field routine that optimizes computer speed. The Olson-Pfitzer 1977 tilt dependent model is such a routine. It, however, uses the Barraclough internal field routine and thus is not appropriate for the CRRES effort. The IGRF routines using the modern field coefficients were obtained from the National Space Sciences Data Center (NSSDC). These routines are, however,

considerably slower than the routine contained in the original version of the 1977 tilt dependent model. The main field routine contained in the 1977 model is derived from Joe Cain's SPHRC routine. This routine gains additional speed at the expense of some memory. Instead of using indexed loops it explicitly writes out the spherical harmonic expansion terms and thus all of the overhead required to keep track of the various indices is abolished. It is this authors opinion that this version of representing the main field is inherently 50% faster than any other representation. The version used in the 1977 tilt dependent model has the Gauss normalized Barraclough coefficients built into the model. It, furthermore, has a term dropping algorithm, that drops the higher order terms as distances increases. This results in a considerable savings in computer time.

The IGRF internal field model developed for the CRRES analysis begins with Joe Cain's spherical harmonic expansion. The new IGRF routine has been given the name SPIGRF (SPeed IGRF). Since the IGRF coefficients are for a tenth order expansion, terms up the  $N=11$  are contained in SPIGRF (the Barraclough model only had 10 terms). The first time SPIGRF is called, it calls a routine called FLDCOF. FLDCOF reads the appropriate IGRF coefficient sets, interpolates to the epoch of interest and converts the Schmitt normalized IGRF coefficients to Gauss normalized coefficients. If during a subsequent call, the date has changed by more than 0.1 year, FLDCOF is once again called to update the coefficients to the new epoch. It is not computationally efficient to update the coefficients for minor changes in time. In fact it might be appropriate for the CRRES mission to select a specific date and use coefficients for the internal magnetic field that do not change with time. This is a programmatic decision and will have little or no impact on the science unless CRRES continues to function for more than 4 or 5 years.

The term dropping algorithm that is a part of SPIGRF is a smooth algorithm. The algorithm uses predetermined altitudes where specific terms are to be discontinued. Table 1 lists the altitudes and maximum number of terms that are used by SPIGRF.

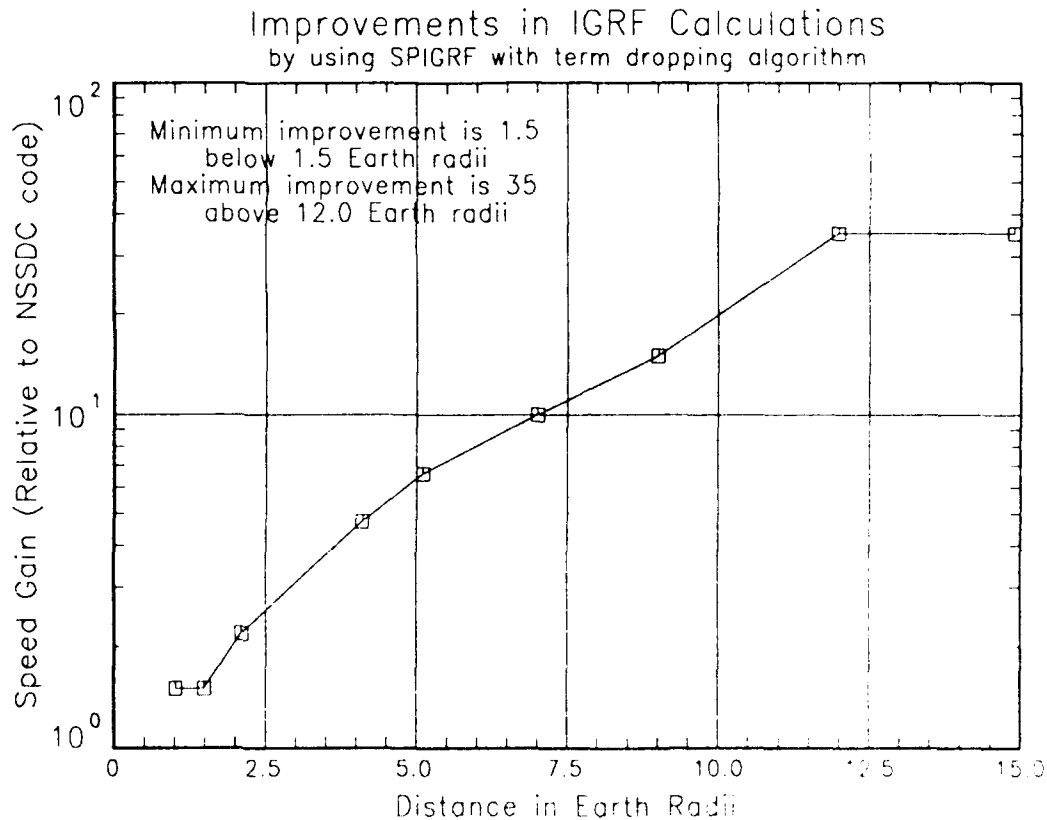
Table 1

Altitude, $R_E$	Number of terms
12.0	2
8.0	3
6.0	4
5.0	5
4.0	6
3.2	7
2.5	8
2.0	9
1.6	10
1.4	11

Thus for altitudes greater than 12  $R_E$  only the dipole term is used. For altitudes less than 1.4  $R_E$  all 11 terms are used. For altitudes between 1.4 and 1.6, the contribution of the  $N=11$  term is linearly reduced from its full value at 1.4 to zero at 1.6. Similarly for all other intervals. The altitude values at which the term dropping takes place was experimentally determined by comparing the truncated model with the untruncated version. The truncated model differs from the untruncated model by no more than 0.1 nanotesla.

This new IGRF code is inherently 1.5 times as fast as the NSSDC code, FELDG, when used with all the terms. The term drop off algorithm significantly improves the speed without sacrificing accuracy. Figure 1 presents the speed advantage of SPIGRF when compared to the original NSSDC code. At  $3.0 R_E$  it is 3 times as fast as FELDG, 7 times as fast at  $5 R_E$ , 10 times as fast at  $7 R_E$ , and 35 times as fast at  $12 R_E$ . Since the term drop off algorithm removes the effect of a term smoothly, there are no discontinuities in the field. For a typical CRRES orbit, this version of IGRF should have an average speed advantage of 7 or 8.

**Figure 1**



A listing and a brief description of the calling sequence for SPIGRF is given in Appendix A.

## *2.2 Internal plus External Field*

The new routine, SPIGRF, was combined with the remaining routines of the 1977 tilt dependent magnetic field model to produce a high speed quiet time magnetic field model that uses the IGRF coefficients. The name of the entire file that contains the tilt dependent model, SPIGRF, and a test routine was given the name BMNIGRF.

The execution speed of the new fast IGRF code, SPIGRF, plus the 1977 tilt dependent external model is faster everywhere than the old internal IGRF code, FELDG, without the external model. At  $1.4 R_E$  or less the speed advantage is 1.2, at  $2 R_E$  it is 1.05, at  $6 R_E$  it is 1.6 and at  $10 R_E$  it is 2.0. Thus calculating B,L using the external and internal field routines is faster than calculating a B,L based on the internal field alone using the older IGRF routines.

Note: The external field model presently used for the initial CRRES studies is the 1977 quiet time tilt dependent model. The dynamic model, which will be used to study the outer zone as a function of magnetospheric compression, will replace the quiet time model at the appropriate time.

Appendix B gives a listing of the BMNIGRF test routine, the 1977 tilt dependent routine, BXYZMU, and the various routines required to combine the external and internal magnetic fields. The internal field routines are described in Appendix A.

## *2.3 A Pitch Angle Dependent B,L Routine*

In order to adequately represent directional data, it is necessary to define the first and second invariant for each directional measurement. At the present time the current B,L routines calculate the invariant for a particle that mirrors at the location of the satellite. All other particles will of course have different first and second

invariant. The first invariant is simply the mirror point magnetic field of the particle and thus  $B_{\text{mir}}$  is given by

$$B_{\text{mir}} = \frac{B_{\text{local}}}{\sin^2(\alpha_{\text{local}})} \quad (1)$$

where  $B_{\text{local}}$  is the magnetic field at the location of the measurement and  $\alpha_{\text{local}}$  is the local pitch angle of the measurement. Thus the first invariant can be easily calculated for each directional measurement at a specific location.

The second, or integral invariant,  $J$ , is given by

$$J = \int_{B_{\text{mir}}}^{B_{\text{mir}}} \sqrt{1 - \frac{B}{B_{\text{mir}}}} ds \quad (2)$$

This is a line integral over the bounce path of the particle and is calculated from one mirror point to the conjugate mirror point in the other hemisphere. If one needs to calculate the second invariant for more than one pitch angle, more than one integral must be evaluated. For a given line integral along a magnetic line of force between two conjugate mirror points, many calls must be made to the magnetic field subroutines. Since these routines contain spherical harmonic expansions or some other equally complex expansions for the internal field, the number of calls to the magnetic field routines must be minimized. If two particles have pitch angle  $\alpha_1$  and pitch angle  $\alpha_2$  and  $\alpha_1$  is greater than  $\alpha_2$ , then the bounce path length of the pitch angle  $\alpha_2$  particle is longer than that of the  $\alpha_1$  particle. However, both particles will follow the same bounce path in the region of overlap. That is the line along which the integral is performed for pitch angle  $\alpha_1$  stops at  $B_{\text{mir}1}$  but that for pitch angle  $\alpha_2$  continues on through  $B_{\text{mir}1}$  to  $B_{\text{mir}2}$ . Unfortunately since  $B_{\text{mir}}$  is inside the integral sign the value of the integral along the line differs for the two particles.

Maximum computer speed is obtained by dividing the invariant calculation into two parts. The first part calculates the path along the line of force and saves all of the pertinent parameters, and the second part calculates the integral invariant for each of the pitch angles. The multiple pitch angle invariant routine, INVARM, can calculate the first and second invariant of an unspecified number of pitch angles. The angles must be greater than zero (a pitch angle of zero would give an infinite first invariant) and less than or equal to 90 degrees. The pitch angle array must be sorted from biggest to smallest (i.e. 90,80,70,...). The line integral part of INVARM steps along a line of force with a step size that is dependent on the curvature of the line of force until the first  $B_{\max}$  is reached. At each step in the integration the program calculates the step size as a function of the curvature of the field line. It also approximates from the present progress of the integration the step size needed to reach  $B_{\max}$ . It then chooses the smaller of the two steps. It attempts to get close to  $B_{\max}$  without stepping past it on the first approach. It is important not to exceed  $B_{\max}$  since the argument of the integral become imaginary if  $B_{\max}$  is exceeded. The step size algorithm appears to work reasonably well and achieves an almost 100% success rate in not overstepping  $B_{\max}$  on the first try. If  $B_{\max}$  is exceeded the routine backs up and attempts to determine a step 'close' to  $B_{\max}$  but smaller than  $B_{\max}$ .

When the integration is first started, the routine first moves in the decreasing B direction in order that it can find the precise value and location of the minimum B. When minimum B is passed, the interpolation routine determines a precise value for  $B_{\min}$  and also determines the magnetic longitude of minimum B. Once  $B_{\max}$  has been found in one direction, the integral is re-started at the original location and that part of the line to the other mirror point is evaluated. Once the field line for the first pitch angle is found between the two mirror points, the values stored by the field line

code are used to evaluate the integral for the second invariant for the first pitch angle. To calculate the invariant for additional pitch angles, the field line portion of the routine is reentered and the line integration continues from the  $B_{\max}$  stopping point of the previous pitch angle. The integration continues until the field line up to but not exceeding  $B_{\max}$  of the next angle is determined. The integral for the second invariant is then calculated. This continues until the invariant of all of the pitch angles are determined or until one of the mirror points, either north or south is below  $1.03 R_E$ , or the maximum number of steps is exceeded, or until  $13 R_E$  is exceeded. Each subsequent calculation utilizes all of the calculated values of the field strengths and step locations of the previous pitch angle, and thus the number of calls to the magnetic field line routines is minimized. For example, the computer time required to calculate the invariant for 18 pitch angles (90, 85, 80, 75,...,5) is approximate 2 to 3 times as long as the time required to calculate the invariant for the single pitch angle of 20 degrees.

The integration uses Gill's method of Runge-Kutta integration. This is a fourth order procedure and the error goes as step size to the fourth order. An internal error control parameter can be adjusted to control the errors. This parameter is set to give the "L" parameter an accuracy of approximately 0.002. The maximum number of steps is 100. Since it is a fourth order procedure, up to 400 calls to the magnetic field routines are possible. Typically on the order 10 - 15 steps are required for a single pitch angle that mirror far off the equator (i.e. a pitch angle of 20 degrees at an L of 5.0). When the invariant for 18 pitch angles are calculated an additional step may be needed at both the northern and southern conjugate points for each additional pitch angle. If successive pitch angles are very close together, the interpolation routine may be able to calculate the next invariant without the need of an additional step.

When the invariant routine calculates the second invariant it also integrates the total column density of the atmosphere between the mirror points. The density integral uses the atmospheric density function developed for the Air Force Office of Scientific Research. This function is given by

$$\text{density} = 2.7 \times 10^{-11} \exp[(120-z)/(\text{CON} \cdot \sqrt{z-103})] \quad (3)$$

Where  $z$  is the altitude in kilometer and CON is an F10.7 dependent parameter (70 - 240) and is given by

$$\text{CON} = 0.99 + 0.518 \cdot \sqrt{\text{F10.7}/55} \quad (4)$$

Outside of  $3.0 R_E$  or outside of a specified distance, the density function is arbitrarily set to zero, since the function has little validity above 1000 km altitude. It is, however, a smoothly decreasing function and can thus be used as an organizing parameter for atmospheric mirror depth up to  $3.0 R_E$ .

Figures 2 - 5 are copies of the printouts for the calculation of the first and second invariant, and the 'L' parameter, and the density totals for a set of test conditions. Each page has two conditions. The top run uses the internal field only and the bottom run uses internal plus external field. All runs are started at latitude = 0, longitude = 1.0, Day of year = 1 and Universal time = 0. Figure 2 is started at an altitude of  $1.5 R_E$ . Both the internal and internal plus external runs give the same result since the external field is unimportant in this region of space. The small variations in L between the various pitch angle are due to the inaccuracies in the integration and more importantly to the accuracy and inherent approximate definition of the L expansion (see Hilton, J. Geophys. Res. 72, 6952, 1971). Pitch angles smaller than 35 degrees have their mirror point below 200 km and the invariant is thus not be evaluated. The internal field expansion diverges for

distances less than  $1.0 R_E$ , and thus mirror points below 1.0 cannot be assigned a second invariant. A -1.0 in any of the parameters indicates that the mirror point is too low in the atmosphere to calculate the invariant and assume that the particle is not trapped. A value of 100 indicates an open field line. As the altitude increases in Figures 3, 4 and 5, differences between the top run with internal field only and the internal plus external field run become increasingly large. The bottom run in Figure 5, a run that calculates the invariant of a measurement at  $7.5 R_E$ , shows that shell splitting at  $7.5 R_E$  is almost a full  $R_E$ .

The second to the last column in the printout shows the atmospheric density parameter. As the integration proceeds down the field line, the integration sums the atmospheric density producing a column number density for the amount of atmosphere a particle encounters as it bounces between the two mirror points. This number given in  $\text{grams/cm}^2$  is intended to represent the importance of the atmosphere as a loss mechanism for the trapped particles. One observation can already be made from figure 2; 5 degree bins near the loss cone may not be an adequately fine resolution. As can be seen from figure 2, a 5 degree change in pitch angle (40 degrees to 35 degrees) causes the atmospheric column density to change by over two orders of magnitude. The next 5 degree bin mirrors below 200 km. Figure 3 gives a 7 order of magnitude change in density encountered in the last 5 degree pitch angle bin. These numbers are an indicator on the expected sharpness of the atmospheric loss cone.

The last column displayed in the printouts shows the equatorial pitch for the specified particle at the present location. It is given by

$$\alpha_{eq} = \sin^{-1} \left[ \sqrt{\frac{B_{min}}{B_{local}}} \cdot \sin(\alpha_{local}) \right] \quad (5)$$

where  $\alpha_{eq}$  is the equatorial pitch angle and  $\alpha_{local}$  is the local pitch angle. It is important to remember that the equatorial pitch angle of a particle is not an invariant. The equatorial pitch angle of a particle changes as the particle drifts around the earth. This effect is most important at large distances where the earth's field becomes more asymmetric.

INVARM, efficiently calculates the first and second invariant of numerous pitch angles at a single satellite position. It also calculates the effective L's for the given set of invariant. It, furthermore, determines the actual minimum B field along the field line, the magnetic latitude of the observation point and the magnetic longitude where the field line crosses the magnetic equator. It also provides the column density of the atmosphere between the mirror points and thus is able to estimate the amount of scattering or absorption that can take place at the specified pitch angle. INVARM provides a complete characterization of all of the pertinent magnetic parameters for any set of pitch angles anywhere within the stable trapping region.

Appendix C lists routine INVARM, a test routines, and the various subroutines and functions required for its correct operation. The magnetic field routines required to define the field are described in Appendix A and B.

### **3.0 Summary**

The new pitch angle dependent invariant code with its ability to calculate atmospheric mirror point depth will substantially improve our ability to organize the directional charged particle data from the CRRES satellite and develop the next generation radiation belt models. Considerable effort was expended to achieve an efficient code that minimizes computer time. The speed of the IGRF internal model was considerably improved and the invariant code is highly optimized. The success of this code must now be verified by organizing the CRRES data with this code.

Figure 2

Lat = .0 Long = 1.0 R = 1.5  
 Year = 1990.0 Day = 1. UT = .00 Field = INT  
 Blocal = .08314 Bmin = .08170 Mlat = 3.977 Mlong = 346.458

P. Angle	B mir	2nd Inv.	L	Density	Eq. Pitch Angle
90.0	.08314	.01980	1.548	3.49255E-17	82.45
85.0	.08377	.03084	1.549	7.59682E-17	80.95
80.0	.08572	.05440	1.548	6.75144E-17	77.49
75.0	.08911	.09770	1.547	1.13693E-16	73.25
70.0	.09415	.15871	1.547	2.15133E-16	68.68
65.0	.10121	.23789	1.547	4.75860E-16	63.96
60.0	.11085	.33591	1.546	1.42643E-15	59.15
55.0	.12390	.45367	1.545	5.81409E-15	54.30
50.0	.14167	.59234	1.545	4.52273E-14	49.41
45.0	.16627	.75347	1.544	7.56966E-13	44.51
40.0	.20121	.93914	1.544	4.50108E-11	39.58
35.0	.25270	1.15224	1.544	7.44210E-08	34.65
30.0	-1.00000	-1.00000	-1.000	-1.00000E+00	29.71
25.0	-1.00000	-1.00000	-1.000	-1.00000E+00	24.77
20.0	-1.00000	-1.00000	-1.000	-1.00000E+00	19.82
15.0	-1.00000	-1.00000	-1.000	-1.00000E+00	14.87
10.0	-1.00000	-1.00000	-1.000	-1.00000E+00	9.91
5.0	-1.00000	-1.00000	-1.000	-1.00000E+00	4.96

Lat = .0 Long = 1.0 R = 1.5  
 Year = 1990.0 Day = 1. UT = .00 Field = IN+EX  
 Blocal = .08314 Bmin = .08170 Mlat = 3.977 Mlong = 346.458

P. Angle	B mir	2nd Inv.	L	Density	Eq. Pitch Angle
90.0	.08314	.01980	1.548	3.49255E-17	82.45
85.0	.08377	.03084	1.549	7.59682E-17	80.95
80.0	.08572	.05443	1.548	6.75032E-17	77.49
75.0	.08911	.09772	1.547	1.13681E-16	73.25
70.0	.09415	.15872	1.547	2.15143E-16	68.68
65.0	.10121	.23789	1.547	4.75860E-16	63.96
60.0	.11085	.33591	1.546	1.42642E-15	59.15
55.0	.12390	.45367	1.545	5.81420E-15	54.30
50.0	.14167	.59234	1.545	4.52266E-14	49.41
45.0	.16627	.75347	1.544	7.56985E-13	44.51
40.0	.20121	.93914	1.544	4.50081E-11	39.58
35.0	.25270	1.15224	1.544	7.44241E-08	34.65
30.0	-1.00000	-1.00000	-1.000	-1.00000E+00	29.71
25.0	-1.00000	-1.00000	-1.000	-1.00000E+00	24.77
20.0	-1.00000	-1.00000	-1.000	-1.00000E+00	19.82
15.0	-1.00000	-1.00000	-1.000	-1.00000E+00	14.87
10.0	-1.00000	-1.00000	-1.000	-1.00000E+00	9.91
5.0	-1.00000	-1.00000	-1.000	-1.00000E+00	4.96

Figure 3

Lat = .0 Long = 1.0 R = 3.5  
 Year = 1990.0 Day = 1. UT = .00 Field = INT  
 Bloclal = .00671 Bmin = .00670 Mlat = 3.977 Mlong = 347.074

P. Angle	B mir	2nd Inv.	L	Density	Eq. Pitch Angle
90.0	.00671	.00478	3.563	0.00000E+00	87.54
85.0	.00676	.02515	3.563	0.00000E+00	84.43
80.0	.00692	.08661	3.564	0.00000E+00	79.71
75.0	.00719	.18824	3.564	0.00000E+00	74.80
70.0	.00760	.33149	3.564	0.00000E+00	69.86
65.0	.00817	.51729	3.564	0.00000E+00	64.89
60.0	.00895	.74715	3.565	0.00000E+00	59.91
55.0	.01000	1.02299	3.565	0.00000E+00	54.92
50.0	.01143	1.34728	3.565	0.00000E+00	49.94
45.0	.01342	1.72315	3.565	3.61182E-31	44.95
40.0	.01624	2.15459	3.566	5.97057E-30	39.96
35.0	.02039	2.64682	3.566	1.14628E-28	34.96
30.0	.02684	3.20675	3.567	4.36298E-27	29.97
25.0	.03756	3.84408	3.568	4.41615E-25	24.98
20.0	.05735	4.57326	3.570	1.96738E-22	19.98
15.0	.10015	5.41832	3.574	1.23996E-18	14.99
10.0	.22250	6.42566	3.581	9.83762E-12	9.99
5.0	-1.00000	-1.00000	-1.000	-1.00000E+00	5.00

Lat = .0 Long = 1.0 R = 3.5  
 Year = 1990.0 Day = 1. UT = .00 Field = IN+EX  
 Bloclal = .00629 Bmin = .00628 Mlat = 3.977 Mlong = 347.076

P. Angle	B mir	2nd Inv.	L	Density	Eq. Pitch Angle
90.0	.00629	.00323	3.641	0.00000E+00	87.86
85.0	.00633	.02177	3.640	0.00000E+00	84.56
80.0	.00648	.07700	3.637	0.00000E+00	79.78
75.0	.00674	.16928	3.632	0.00000E+00	74.85
70.0	.00712	.29965	3.625	0.00000E+00	69.89
65.0	.00765	.46972	3.617	0.00000E+00	64.91
60.0	.00838	.68166	3.607	0.00000E+00	59.93
55.0	.00937	.93820	3.597	0.00000E+00	54.94
50.0	.01071	1.24271	3.587	0.00000E+00	49.95
45.0	.01257	1.59937	3.577	7.74855E-32	44.96
40.0	.01521	2.01326	3.567	3.16436E-30	39.97
35.0	.01911	2.49064	3.559	5.99803E-29	34.97
30.0	.02514	3.03944	3.552	2.16502E-27	29.98
25.0	.03520	3.67102	3.547	2.05865E-25	24.98
20.0	.05374	4.39990	3.545	9.01949E-23	19.99
15.0	.09384	5.24888	3.545	5.15603E-19	14.99
10.0	.20847	6.26971	3.550	2.36695E-12	9.99
5.0	-1.00000	-1.00000	-1.000	-1.00000E+00	5.00

Figure 4

Lat = .0 Long = 1.0 R = 5.5  
 Year = 1990.0 Day = 1. UT = .00 Field = INT  
 Blocal = .00176 Bmin = .00175 Mlat = 3.977 Mlong = 347.274

P. Angle	B mir	2nd Inv.	L	Density	Eq. Pitch Angle
90.0	.00176	.02370	5.570	0.00000E+00	85.61
85.0	.00178	.05570	5.571	0.00000E+00	83.35
80.0	.00182	.15174	5.571	0.00000E+00	79.09
75.0	.00189	.31037	5.572	0.00000E+00	74.39
70.0	.00200	.53408	5.572	0.00000E+00	69.54
65.0	.00215	.82419	5.572	0.00000E+00	64.64
60.0	.00235	1.18302	5.572	0.00000E+00	59.71
55.0	.00263	1.61355	5.572	0.00000E+00	54.76
50.0	.00300	2.11971	5.573	0.00000E+00	49.80
45.0	.00353	2.70611	5.573	0.00000E+00	44.83
40.0	.00427	3.37914	5.573	0.00000E+00	39.86
35.0	.00536	4.14658	5.573	0.00000E+00	34.88
30.0	.00705	5.01889	5.574	0.00000E+00	29.90
25.0	.00987	6.01042	5.575	0.00000E+00	24.92
20.0	.01507	7.14198	5.575	0.00000E+00	19.94
15.0	.02632	8.44591	5.575	3.17060E-28	14.96
10.0	.05847	9.99589	5.578	4.08695E-23	9.97
5.0	.23210	11.96305	5.591	2.22143E-13	4.99

Lat = .0 Long = 1.0 R = 5.5  
 Year = 1990.0 Day = 1. UT = .00 Field = IN+EX  
 Blocal = .00150 Bmin = .00149 Mlat = 3.977 Mlong = 347.279

P. Angle	B mir	2nd Inv.	L	Density	Eq. Pitch Angle
90.0	.00150	.00888	5.875	0.00000E+00	86.92
85.0	.00151	.03287	5.871	0.00000E+00	84.13
80.0	.00154	.10480	5.859	0.00000E+00	79.54
75.0	.00160	.22568	5.838	0.00000E+00	74.69
70.0	.00170	.39743	5.810	0.00000E+00	69.77
65.0	.00182	.62326	5.776	0.00000E+00	64.82
60.0	.00200	.90760	5.736	0.00000E+00	59.86
55.0	.00223	1.25613	5.693	0.00000E+00	54.88
50.0	.00255	1.67608	5.647	0.00000E+00	49.90
45.0	.00299	2.17641	5.602	0.00000E+00	44.92
40.0	.00362	2.76782	5.558	0.00000E+00	39.93
35.0	.00455	3.46351	5.518	0.00000E+00	34.94
30.0	.00599	4.27886	5.484	0.00000E+00	29.95
25.0	.00838	5.23284	5.455	0.00000E+00	24.96
20.0	.01280	6.34978	5.434	0.00000E+00	19.97
15.0	.02235	7.66456	5.418	4.39264E-29	14.98
10.0	.04965	9.24901	5.408	8.57689E-24	9.99
5.0	.19708	11.29810	5.417	2.64089E-14	4.99

Figure 5

Lat = .0 Long = 1.0 R = 7.5  
 Year = 1990.0 Day = 1. UT = .00 Field = INT  
 Blocal = .00070 Bmin = .00070 Mlat = 3.977 Mlong = 347.369

P. Angle	B mir	2nd Inv.	L	Density	Eq. Pitch Angle
90.0	.00070	.04747	7.576	0.00000E+00	84.68
85.0	.00071	.09120	7.577	0.00000E+00	82.71
80.0	.00072	.22136	7.578	0.00000E+00	78.69
75.0	.00075	.43727	7.578	0.00000E+00	74.11
70.0	.00080	.74148	7.579	0.00000E+00	69.33
65.0	.00086	1.13600	7.579	0.00000E+00	64.48
60.0	.00094	1.61743	7.576	0.00000E+00	59.58
55.0	.00105	2.20718	7.579	0.00000E+00	54.65
50.0	.00120	2.88932	7.576	0.00000E+00	49.71
45.0	.00141	3.68936	7.578	0.00000E+00	44.75
40.0	.00170	4.60022	7.577	0.00000E+00	39.79
35.0	.00214	5.64240	7.577	0.00000E+00	34.83
30.0	.00281	6.82682	7.577	0.00000E+00	29.86
25.0	.00393	8.17300	7.577	0.00000E+00	24.89
20.0	.00601	9.70984	7.578	0.00000E+00	19.91
15.0	.01049	11.48335	7.578	0.00000E+00	14.93
10.0	.02330	13.59271	7.583	1.81184E-29	9.96
5.0	.09250	16.22668	7.587	1.54025E-20	4.98

Lat = .0 Long = 1.0 R = 7.5  
 Year = 1990.0 Day = 1. UT = .00 Field = IN+EX  
 Blocal = .00056 Bmin = .00056 Mlat = 3.977 Mlong = 347.516

P. Angle	B mir	2nd Inv.	L	Density	Eq. Pitch Angle
90.0	.00056	.00053	8.130	0.00000E+00	89.31
85.0	.00057	.02219	8.119	0.00000E+00	84.95
80.0	.00058	.09740	8.091	0.00000E+00	79.98
75.0	.00060	.22835	8.047	0.00000E+00	74.98
70.0	.00064	.41436	7.985	0.00000E+00	69.99
65.0	.00069	.67362	7.915	0.00000E+00	64.99
60.0	.00075	1.00715	7.834	0.00000E+00	59.99
55.0	.00084	1.41840	7.744	0.00000E+00	54.99
50.0	.00096	1.93944	7.657	0.00000E+00	50.00
45.0	.00113	2.56532	7.568	0.00000E+00	45.00
40.0	.00136	3.33051	7.489	0.00000E+00	40.00
35.0	.00171	4.25138	7.420	0.00000E+00	35.00
30.0	.00226	5.35211	7.365	0.00000E+00	30.00
25.0	.00316	6.66066	7.326	0.00000E+00	25.00
20.0	.00482	8.21100	7.301	0.00000E+00	20.00
15.0	.00842	10.04846	7.289	0.00000E+00	15.00
10.0	.01870	12.27038	7.290	1.86371E-30	10.00
5.0	.07423	14.73075	7.168	7.07675E-22	5.00

## Appendix A

### Internal Magnetic Field Subroutines

Subroutine SPIGRF is a fast version of the IGRF internal field subroutine. Instead of using DO loops to expand the spherical harmonic coefficients, it writes out the expansion according to a routine developed by J. Cain. This version of the routine developed for the CRRES program is not designed for stand alone use and is designed to be a part of a total magnetic field program that includes the internal as well as the external magnetic field. The calling arguments are thus passed in a common block and the geomagnetic latitude and longitude are passed via their sines and cosines. This technique saves computer time. A stand-alone version would be much easier to use if the calling variables were transmitted as standard subroutine arguments. If an easy to use stand alone version is needed, a simple change to the first few lines of the code can produce a very efficient stand-alone internal field code.

The method of coding the magnetic field in SPIGRF is inherently faster than a DO loop version. Furthermore, the addition of a term dropping algorithm increases the speed as much as a factor of 35. The variable CONA dimensioned 11 contains the altitudes at which successive terms are to be dropped. A linear interpolation between these distance values drops the terms off smoothly. The smooth feature is important since it prevents discontinuities in the magnetic field from disrupting the integration steps and the interpolation algorithms in the field line tracing program.

#### A.1 Calling Sequence

The transfer of information between SPIGRF and the calling routine is performed via labeled COMMON GCOM.

#### INPUT values

YEARI	Contains the year for which the coefficients are to be determined. The supplied coefficients are valid from 1945 to the present. The 1945 coefficients are used for years earlier than 1945. Predicting far into the future is hazardous since the time derivative terms do not have long term validity. If YEARI is changed by .1 years since the last call a new updated set of coefficients is calculated. It is suggested that YEARI be used to set the desired epoch and then left constant.
NMAXN	Contains the number of terms desired. If this is left 0 then the full 11 term expansion of IGRF is used. If NMAXN is between 2 and 10, then the maximum number of terms is set to that number. Term dropping still takes place for larger distances.
ST	Sine of the geographic <b>co-latitude</b>
CT	Cosine of the geographic <b>co-latitude</b>

SPH        Sine of the geographic longitude.  
CPH        Cosine of the geographic longitude  
AOR         $6371.2/R$ , where R is the distance from the center of the Earth in km

**OUTPUT values**

BR        The radial component of the magnetic field in gauss (ie. nanotesla)  
BT        Theta component (south pointing) component  
BP        Phi component (East)

Each time the field coefficients are updated, the value of the new dipole moment is stored in labeled COMMON /MOMENT/ XM. It is thus available for use by any routine that needs it, such as the L value program.

NOTE: SPIGRF uses a true spherical coordinate system with the z axis along the geographic north pole, the x axis through the longitude of Greenwich. R, Theta and Phi are the true spherical polar coordinates.

The routine will read several of the IGRF Coefficient sets. The coefficient sets are listed at the end of this appendix. Subroutine FLDCOF sets the FORTRAN logical unit for reading the coefficients to 11. The actual read statement for reading the coefficients are found in subroutine GETGAU.

```

SUBROUTINE SPIGRF
C
C   VERSION 4/91
C   WRITTEN BY K.A. PFITZER (714) 896-3231
C   SPIGRF IS A MODIFIED VERSION OF J.C. CAIN'S 14 TERM FAST SPHRC
C   ROUTINE.
C   IT HAS BEEN SHORTENED TO 11 TERMS FOR CONSISTENCY WITH THE IGRF
C   COEFFICIENT SET.
C   IT HAS A TRUNCATION FOR LARGE R - THE TRUNCATION BETWEEN TERMS
C   IS SMOOTH AND MAINTAINS AN ACCURACY OVER THE NON-TRUNCATED VERSION
C   OF BETTER THAN .1 NANOTESLA.
C   DEPENDING ON ALTITUDE THIS VERSION RUNS FROM 1.5 TO 35.0 TIMES AS FAST
C   AS THE STANDARD SCHMITT NORMLIZED IGRF ROUTINES
C   THE SUPPORT ROUTINES READ THE STANDARD IGRF COEFFICIENTS AND
C   CONVERT THEM TO GAUSS NORMALIZED FOR USE BY THIS ROUTINE
C
C
C   The first time the routine is called, the routine calls routine
C   call routine FLDCOF to obtain the correct IGRF coefficients. If
C   the date changes by more than .1 year the coefficients are updated,
C   new coefficients are obtained if required.
C
C   INPUT -- COMMON BLOCK GCOM
C   YEAR1 IS THE YEAR, IF YEAR1 CHANGES, THE COEFFICIENTS ARE
C   UPDATED.
C   ST SINE OF THE GEOGRAPHIC CO-LATITUDE.
C   CT COSINE OF THE GEOGRAPHIC CO-LATITUDE.
C   SPH SINE OF THE GEOGRAPHIC LONGITUDE.
C   CPH COSINE OF THE GEOGRAPHIC LONGITUDE.
C   AOR 6371.2/R, WHERE R IS THE GEOCENTRIC DISTANCE IN KM FROM
C   THE CENTER OF THE EARTH.
C   NMAXN MAXIMUM NUMBER OF TERMS TO BE USED (MUST BE LESS OR
C   EQUAL TO 11). THIS ROUTINE PRESETS IT TO 11
C   NMAXN OF 11 CORRESPONDS TO THE 10TH ORDER IGRF MODELS
C   IF NMAXN IS >2 AND <11, NMAXN TERMS ARE USED, ELSE THE
C   NUMBER OF TERMS USED IS 11 OR THE MAXIMUM TERMS IN THE
C   IGRF DATA SET.
C   OUTPUT -- COMMON BLOCK GCOM
C   BR RADIAL COMPONENT OF FIELD IN GAUSS.
C   BT THETA COMPONENT (SOUTH POINTING) COMPONENT.
C   BP PHI COMPONENT (EAST)
C
C   DIMENSION G(11,11),CONST(11,11),FM(11),FN(11)
C   COMMON /MODEL/G
C   COMMON /GCOM/ ST,CT,SPH,CPH,AOR,BT,BP,BR,NMAXN,YEAR1
C   COMMON /MOMENT/XM
C   DIMENSION CONA(11)
C   DATA YRLAST /-12345./
C   DATA IFIRST/0/
C   DATA CONA/0.,12.0,8.0,6.0,5.0,4.0,3.2,2.5,2.0,1.6,1.4/
C
C   SET UP INITIAL CONSTANTS DURING FIRST CALL
C   IF(IFIRST.NE.0) GO TO 199
C   IFIRST=1
C   FM(1)=0
C   DO 6 N=2,11
C   FM(N)=N-1
C   FN(N)=N
C   DO 6 M=1,N
C   CONST(N,M)=FLOAT((N-2)**2-(M-1)**2)/FLOAT((2*N-3)*(2*N-5))
C
C   SET UP THE COEFFICIENTS
C   IF YEAR1 HAS CHANGED BY MORE THAN .1 YEAR UPDATE THE COEFFICIENTS
C

```

```

199 IF (ABS (YRLAST-YEAR1) .LT.0.1) GO TO 230
CALL FLDCOF (YEAR1,DIMO,MAXN)
XM=DIMO/1.0E5
YRLAST=YEAR1
C
230 NMAX=MAXN
IF (NMAXN.GE.2.AND.NMAXN.LT.MAXN) NMAX=NMAXN
AR=AOR*AOR*AOR
C2=G(2,2)*CPH+G(1,2)*SPH 1-00006
BR=-(AR+AR)*(G(2,1)*CT+C2*ST) 1-00007
BT=AR*(C2*CT-G(2,1)*ST) 1-00008
BP=AR*(G(1,2)*CPH-G(2,2)*SPH) 1-00009
IF (NMAX.LE.2) RETURN 1-00010
R=1./AOR 1-00011
IF (R.GT.CONA(2)) RETURN
CON=0.
SP2=SPH 1-00012
CP2=CPH 1-00013
P21=CT 1-00014
P22=ST 1-00015
DP21=-ST 1-00016
DP22=CT 1-00017
N=3
SP3=(SP2+SP2)*CP2 1-00019
CP3=(CP2+SP2)*(CP2-SP2) 1-00020
P31=CT*P21-CONST(3,1) 1-00021
P32=CT*P22 1-00022
P33=ST*P22 1-00023
DP31=-P32-P32 1-00024
DP32=CT*DP22-P33 1-00025
DP33=-DP31 1-00026
C2=G(3,2)*CP2+G(1,3)*SP2 1-00027
C3=G(3,3)*CP3+G(2,3)*SP3 1-00028
AR=AOR*AR 1-00029
XR=BR-FN(3)*AR*(G(3,1)*P31+C2*P32+C3*P33) 1-00030
XT=BT+AR*(G(3,1)*DP31+C2*DP32+C3*DP33) 1-00031
XP=BP-AR*(FM(2)*(G(3,2)*SP2-G(1,3)*CP2)*P21+FM(3)*(G(3,3)*SP3-G(2,
+3)*CP3)*P22) 1-00032
BP=BP*ST 1-00033
XP=XP*ST 1-00035
IF (NMAX.LE.3) GO TO 21 1-00035
IF (R.GT.CONA(3)) GO TO 20
N=4
SP4=SPH*CP3+CPH*SP3 1-00037
CP4=CPH*CP3-SPH*SP3 1-00038
P41=CT*P31-CONST(4,1)*P21 1-00039
DP41=CT*DP31-ST*P31-CONST(4,1)*DP21 1-00040
P42=CT*P32-CONST(4,2)*P22 1-00041
DP42=CT*DP32-ST*P32-CONST(4,2)*DP22 1-00042
P43=CT*P33 1-00043
DP43=CT*DP33-ST*P33 1-00044
P44=ST*P33 1-00045
DP44=FM(4)*P43 1-00046
C2=G(4,2)*CP2+G(1,4)*SP2 1-00047
C3=G(4,3)*CP3+G(2,4)*SP3 1-00048
C4=G(4,4)*CP4+G(3,4)*SP4 1-00049
AR=AOR*AR 1-00050
BR=XR-FN(4)*AR*(G(4,1)*P41+C2*P42+C3*P43+C4*P44) 1-00051
BT=XT+AR*(G(4,1)*DP41+C2*DP42+C3*DP43+C4*DP44) 1-00052
BP=XP-AR*(FM(2)*(G(4,2)*SP2-G(1,4)*CP2)*P42+FM(3)*(G(4,3)*SP3-G(2,
+4)*CP3)*P43+FM(4)*(G(4,4)*SP4-G(3,4)*CP4)*P44) 1-00053
IF (NMAX.LE.4) GO TO 11 1-00054
IF (R.GT.CONA(4)) GO TO 10
N=5

```

SP5=(SP3+SP3)*CP3	1-00057
CP5=(CP3+SP3)*(CP3-SP3)	1-00058
P51=CT*P41-CONST(5,1)*P31	1-00059
DP51=CT*DP41-ST*P41-CONST(5,1)*DP31	1-00060
P52=CT*P42-CONST(5,2)*P32	1-00061
DP52=CT*DP42-ST*P42-CONST(5,2)*DP32	1-00062
P53=CT*P43-CONST(5,3)*P33	1-00063
DP53=CT*DP43-ST*P43-CONST(5,3)*DP33	1-00064
P54=CT*P44	1-00065
DP54=CT*DP44-ST*P44	1-00066
P55=ST*P44	1-00067
DP55=FM(5)*P54	1-00068
C2=G(5,2)*CP2+G(1,5)*SP2	1-00069
C3=G(5,3)*CP3+G(2,5)*SP3	1-00070
C4=G(5,4)*CP4+G(3,5)*SP4	1-00071
C5=G(5,5)*CP5+G(4,5)*SP5	1-00072
AR=AOR*AR	1-00073
XR=BR-FN(5)*AR*(G(5,1)*P51+C2*P52+C3*P53+C4*P54+C5*P55)	1-00074
XT=BT+AR*(G(5,1)*DP51+C2*DP52+C3*DP53+C4*DP54+C5*DP55)	1-00075
XP=BP-AR*(FM(2)*(G(5,2)*SP2-G(1,5)*CP2)*P52+FM(3)*(G(5,3)*SP3-G(2,1-00076	
+5)*CP3)*P53+FM(4)*(G(5,4)*SP4-G(3,5)*CP4)*P54+FM(5)*(G(5,5)*SP5-G(1-00077	
+4,5)*CP5)*P55)	1-00078
IF(NMAX.LE.5) GO TO 21	
IF(R.GT.CONA(5)) GO TO 20	
N=6	
SP6=SPH*CP5+CPH*SP5	1-00081
CP6=CPH*CP5-SPH*SP5	1-00082
P61=CT*P51-CONST(6,1)*P41	1-00083
DP61=CT*DP51-ST*P51-CONST(6,1)*DP41	1-00084
P62=CT*P52-CONST(6,2)*P42	1-00085
DP62=CT*DP52-ST*P52-CONST(6,2)*DP42	1-00086
P63=CT*P53-CONST(6,3)*P43	1-00087
DP63=CT*DP53-ST*P53-CONST(6,3)*DP43	1-00088
P64=CT*P54-CONST(6,4)*P44	1-00089
DP64=CT*DP54-ST*P54-CONST(6,4)*DP44	1-00090
P65=CT*P55	1-00091
DP65=CT*DP55-ST*P55	1-00092
P66=ST*P55	1-00093
DP66=FM(6)*P65	1-00094
C2=G(6,2)*CP2+G(1,6)*SP2	1-00095
C3=G(6,3)*CP3+G(2,6)*SP3	1-00096
C4=G(6,4)*CP4+G(3,6)*SP4	1-00097
C5=G(6,5)*CP5+G(4,6)*SP5	1-00098
C6=G(6,6)*CP6+G(5,6)*SP6	1-00099
AR=AOR*AR	1-00100
BR=XR-FN(6)*AR*(G(6,1)*P61+C2*P62+C3*P63+C4*P64+C5*P65+C6*P66)	1-00101
BT=XT+AR*(G(6,1)*DP61+C2*DP62+C3*DP63+C4*DP64+C5*DP65+C6*DP66)	1-00102
BP=XP-AR*(FM(2)*(G(6,2)*SP2-G(1,6)*CP2)*P62+FM(3)*(G(6,3)*SP3-G(2,1-00103	
+6)*CP3)*P63+FM(4)*(G(6,4)*SP4-G(3,6)*CP4)*P64+FM(5)*(G(6,5)*SP5-G(1-00104	
+4,6)*CP5)*P65+FM(6)*(G(6,6)*SP6-G(5,6)*CP6)*P66)	1-00105
IF(NMAX.LE.6) GO TO 11	
IF(R.GT.CONA(6)) GO TO 10	
N=7	
SP7=(SP4+SP4)*CP4	1-00108
CP7=(CP4+SP4)*(CP4-SP4)	1-00109
P71=CT*P61-CONST(7,1)*P51	1-00110
DP71=CT*DP61-ST*P61-CONST(7,1)*DP51	1-00111
P72=CT*P62-CONST(7,2)*P52	1-00112
DP72=CT*DP62-ST*P62-CONST(7,2)*DP52	1-00113
P73=CT*P63-CONST(7,3)*P53	1-00114
DP73=CT*DP63-ST*P63-CONST(7,3)*DP53	1-00115
P74=CT*P64-CONST(7,4)*P54	1-00116
DP74=CT*DP64-ST*P64-CONST(7,4)*DP54	1-00117
P75=CT*P65-CONST(7,5)*P55	1-00118

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DP75=CT*DP65-ST*P65-CONST(7,5)*DP55      1-00119
P76=CT*P66      1-00120
DP76=CT*DP66-ST*P66      1-00121
P77=ST*P66      1-00122
DP77=FM(7)*P76      1-00123
C2=G(7,2)*CP2+G(1,7)*SP2      1-00124
C3=G(7,3)*CP3+G(2,7)*SP3      1-00125
C4=G(7,4)*CP4+G(3,7)*SP4      1-00126
C5=G(7,5)*CP5+G(4,7)*SP5      1-00127
C6=G(7,6)*CP6+G(5,7)*SP6      1-00128
C7=G(7,7)*CP7+G(6,7)*SP7      1-00129
AR=AOR*AR      1-00130
XR=BR-FN(7)*AR*(G(7,1)*P71+C2*P72+C3*P73+C4*P74+C5*P75+C6*P76+C7*P1-00131
+77)      1-00132
XT=BT+AR*(G(7,1)*DP71+C2*DP72+C3*DP73+C4*DP74+C5*DP75+C6*DP76+C7*D1-00133
+P77)      1-00134
XP=BP-AR*(FM(2)*(G(7,2)*SP2-G(1,7)*CP2)*P72+FM(3)*(G(7,3)*SP3-G(2,1-00135
+7)*CP3)*P73+FM(4)*(G(7,4)*SP4-G(3,7)*CP4)*P74+FM(5)*(G(7,5)*SP5-G(1-00136
+4,7)*CP5)*P75+FM(6)*(G(7,6)*SP6-G(5,7)*CP6)*P76+FM(7)*(G(7,7)*SP7-1-00137
+G(6,7)*CP7)*P77)      1-00138
IF(NMAX.LE.7) GO TO 21
IF(R.GT.CONA(7)) GO TO 20
N=8
SP8=SPH*CP7+CPH*SP7      1-00141
CP8=CPH*CP7-SPH*SP7      1-00142
P81=CT*P71-CONST(8,1)*P61      1-00143
DP81=CT*DP71-ST*P71-CONST(8,1)*DP61      1-00144
P82=CT*P72-CONST(8,2)*P62      1-00145
DP82=CT*DP72-ST*P72-CONST(8,2)*DP62      1-00146
P83=CT*P73-CONST(8,3)*P63      1-00147
DP83=CT*DP73-ST*P73-CONST(8,3)*DP63      1-00148
P84=CT*P74-CONST(8,4)*P64      1-00149
DP84=CT*DP74-ST*P74-CONST(8,4)*DP64      1-00150
P85=CT*P75-CONST(8,5)*P65      1-00151
DP85=CT*DP75-ST*P75-CONST(8,5)*DP65      1-00152
P86=CT*P76-CONST(8,6)*P66      1-00153
DP86=CT*DP76-ST*P76-CONST(8,6)*DP66      1-00154
P87=CT*P77      1-00155
DP87=CT*DP77-ST*P77      1-00156
P88=ST*P77      1-00157
DP88=FM(8)*P87      1-00158
C2=G(8,2)*CP2+G(1,8)*SP2      1-00159
C3=G(8,3)*CP3+G(2,8)*SP3      1-00160
C4=G(8,4)*CP4+G(3,8)*SP4      1-00161
C5=G(8,5)*CP5+G(4,8)*SP5      1-00162
C6=G(8,6)*CP6+G(5,8)*SP6      1-00163
C7=G(8,7)*CP7+G(6,8)*SP7      1-00164
C8=G(8,8)*CP8+G(7,8)*SP8      1-00165
AR=AOR*AR      1-00166
BR=XR-FN(8)*AR*(G(8,1)*P81+C2*P82+C3*P83+C4*P84+C5*P85+C6*P86+C7*P1-00167
+87+C8*P88)      1-00168
BT=XT+AR*(G(8,1)*DP81+C2*DP82+C3*DP83+C4*DP84+C5*DP85+C6*DP86+C7*D1-00169
+P87+C8*DP88)      1-00170
BP=XP-AR*(FM(2)*(G(8,2)*SP2-G(1,8)*CP2)*P82+FM(3)*(G(8,3)*SP3-G(2,1-00171
+8)*CP3)*P83+FM(4)*(G(8,4)*SP4-G(3,8)*CP4)*P84+FM(5)*(G(8,5)*SP5-G(1-00172
+4,8)*CP5)*P85+FM(6)*(G(8,6)*SP6-G(5,8)*CP6)*P86+FM(7)*(G(8,7)*SP7-1-00173
+G(6,8)*CP7)*P87+FM(8)*(G(8,8)*SP8-G(7,8)*CP8)*P88)      1-00174
IF(NMAX.LE.8) GO TO 11
IF(R.GT.CONA(8)) GO TO 10
N=9
SP9=(SP5+SP6)*CP5      1-00177
CP9=(CP5+CP6)*(CP5-SP5)      1-00178
P91=CT*P81-CONST(9,1)*P71      1-00179
DP91=CT*DP81-ST*P81-CONST(9,1)*DP71      1-00180

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P92=CT*P82-CONST(9,2)*P72	1-00181
DP92=CT*DP82-ST*P82-CONST(9,2)*DP72	1-00182
P93=CT*P83-CONST(9,3)*P73	1-00183
DP93=CT*DP83-ST*P83-CONST(9,3)*DP73	1-00184
P94=CT*P84-CONST(9,4)*P74	1-00185
DP94=CT*DP84-ST*P84-CONST(9,4)*DP74	1-00186
P95=CT*P85-CONST(9,5)*P75	1-00187
DP95=CT*DP85-ST*P85-CONST(9,5)*DP75	1-00188
P96=CT*P86-CONST(9,6)*P76	1-00189
DP96=CT*DP86-ST*P86-CONST(9,6)*DP76	1-00190
P97=CT*P87-CONST(9,7)*P77	1-00191
DP97=CT*DP87-ST*P87-CONST(9,7)*DP77	1-00192
P98=CT*P88	1-00193
DP98=CT*DP88-ST*P88	1-00194
P99=ST*P88	1-00195
DP99=FM(9)*P98	1-00196
C2=G(9,2)*CP2+G(1,9)*SP2	1-00197
C3=G(9,3)*CP3+G(2,9)*SP3	1-00198
C4=G(9,4)*CP4+G(3,9)*SP4	1-00199
C5=G(9,5)*CP5+G(4,9)*SP5	1-00200
C6=G(9,6)*CP6+G(5,9)*SP6	1-00201
C7=G(9,7)*CP7+G(6,9)*SP7	1-00202
C8=G(9,8)*CP8+G(7,9)*SP8	1-00203
C9=G(9,9)*CP9+G(8,9)*SP9	1-00204
AR=AOR*AR	1-00205
XR=BR-FN(9)*AR*(G(9,1)*P91+C2*P92+C3*P93+C4*P94+C5*P95+C6*P96+C7*P97+C8*P98+C9*P99)	1-00206
XT=BT+AR*(G(9,1)*DP91+C2*DP92+C3*DP93+C4*DP94+C5*DP95+C6*DP96+C7*DP97+C8*DP98+C9*DP99)	1-00207
XP=BP-AR*(FM(2)*(G(9,2)*SP2-G(1,9)*CP2)*P92+FM(3)*(G(9,3)*SP3-G(2,9)*CP3)*P93+FM(4)*(G(9,4)*SP4-G(3,9)*CP4)*P94+FM(5)*(G(9,5)*SP5-G(4,9)*CP5)*P95+FM(6)*(G(9,6)*SP6-G(5,9)*CP6)*P96+FM(7)*(G(9,7)*SP7-G(6,9)*CP7)*P97+FM(8)*(G(9,8)*SP8-G(7,9)*CP8)*P98+FM(9)*(G(9,9)*SP9-G(8,9)*CP9)*P99)	1-00210
IF(NMAX.LE.9) GO TO 21	1-00211
IF(R.GT.CONA(9)) GO TO 20	1-00212
N=10	1-00213
SP10=SPH*CP9+CPH*SP9	1-00214
CP10=CPH*CP9-SPH*SP9	1-00217
P101=CT*P91-CONST(10,1)*P81	1-00218
DP101=CT*DP91-ST*P91-CONST(10,1)*DP81	1-00219
P102=CT*P92-CONST(10,2)*P82	1-00220
DP102=CT*DP92-ST*P92-CONST(10,2)*DP82	1-00221
P103=CT*P93-CONST(10,3)*P83	1-00222
DP103=CT*DP93-ST*P93-CONST(10,3)*DP83	1-00223
P104=CT*P94-CONST(10,4)*P84	1-00224
DP104=CT*DP94-ST*P94-CONST(10,4)*DP84	1-00225
P105=CT*P95-CONST(10,5)*P85	1-00226
DP105=CT*DP95-ST*P95-CONST(10,5)*DP85	1-00227
P106=CT*P96-CONST(10,6)*P86	1-00228
DP106=CT*DP96-ST*P96-CONST(10,6)*DP86	1-00229
P107=CT*P97-CONST(10,7)*P87	1-00230
DP107=CT*DP97-ST*P97-CONST(10,7)*DP87	1-00231
P108=CT*P98-CONST(10,8)*P88	1-00232
DP108=CT*DP98-ST*P98-CONST(10,8)*DP88	1-00233
P109=CT*P99	1-00234
DP109=CT*DP99-ST*P99	1-00235
P1010=ST*P99	1-00236
DP1010=FM(10)*P109	1-00237
C2=G(10,2)*CP2+G(1,10)*SP2	1-00238
C3=G(10,3)*CP3+G(2,10)*SP3	1-00239
C4=G(10,4)*CP4+G(3,10)*SP4	1-00240
C5=G(10,5)*CP5+G(4,10)*SP5	1-00241
C6=G(10,6)*CP6+G(5,10)*SP6	1-00242
	1-00243

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C7=G(10,7)*CP7+G(6,10)*SP7                                1-00244
C8=G(10,8)*CP8+G(7,10)*SP8                                1-00245
C9=G(10,9)*CP9+G(8,10)*SP9                                1-00246
C10=G(10,10)*CP10+G(9,10)*SP10                             1-00247
AR=AOR*AR                                                    1-00248
BR=XR-FN(10)*AR*(G(10,1)*P101+C2*P102+C3*P103+C4*P104+C5*P105+C6*P1-00249
+106+C7*P107+C8*P108+C9*P109+C10*P1010)                   1-00250
BT=XT+AR*(G(10,1)*DP101+C2*DP102+C3*DP103+C4*DP104+C5*DP105+C6*DP11-00251
+06+C7*DP107+C8*DP108+C9*DP109+C10*DP1010)                1-00252
BP=XP-AR*(FM(2)*(G(10,2)*SP2-G(1,10)*CP2)*P102+FM(3)*(G(10,3)*SP3-1-00253
+G(2,10)*CP3)*P103+FM(4)*(G(10,4)*SP4-G(3,10)*CP4)*P104+FM(5)*(G(101-00254
+,5)*SP5-G(4,10)*CP5)*P105+FM(6)*(G(10,6)*SP6-G(5,10)*CP6)*P106+FM(1-00255
+7)*(G(10,7)*SP7-G(6,10)*CP7)*P107+FM(8)*(G(10,8)*SP8-G(7,10)*CP8)*1-00256
+P108+FM(9)*(G(10,9)*SP9-G(8,10)*CP9)*P109+FM(10)*(G(10,10)*SP10-G(1-00257
+9,10)*CP10)*P1010)                                         1-00258
IF(NMAX.LE.10) GO TO 11
IF(R.GT.CONA(10)) GO TO 10
N=11                                                         1-00260
SP11=(SP6+SP6)*CP6                                           1-00261
CP11=(CP6+SP6)*(CP6-SP6)                                     1-00262
P111=CT*P101-CONST(11,1)*P91                                1-00263
DP111=CT*DP101-ST*P101-CONST(11,1)*DP91                    1-00264
P112=CT*P102-CONST(11,2)*P92                                1-00265
DP112=CT*DP102-ST*P102-CONST(11,2)*DP92                    1-00266
P113=CT*P103-CONST(11,3)*P93                                1-00267
DP113=CT*DP103-ST*P103-CONST(11,3)*DP93                    1-00268
P114=CT*P104-CONST(11,4)*P94                                1-00269
DP114=CT*DP104-ST*P104-CONST(11,4)*DP94                    1-00270
P115=CT*P105-CONST(11,5)*P95                                1-00271
DP115=CT*DP105-ST*P105-CONST(11,5)*DP95                    1-00272
P116=CT*P106-CONST(11,6)*P96                                1-00273
DP116=CT*DP106-ST*P106-CONST(11,6)*DP96                    1-00274
P117=CT*P107-CONST(11,7)*P97                                1-00275
DP117=CT*DP107-ST*P107-CONST(11,7)*DP97                    1-00276
P118=CT*P108-CONST(11,8)*P98                                1-00277
DP118=CT*DP108-ST*P108-CONST(11,8)*DP98                    1-00278
P119=CT*P109-CONST(11,9)*P99                                1-00279
DP119=CT*DP109-ST*P109-CONST(11,9)*DP99                    1-00280
P1110=CT*P1010                                              1-00281
DP1110=CT*DP1010-ST*P1010                                   1-00282
P111=ST*P1010                                               1-00283
DP1111=FM(11)*P1110                                         1-00284
C2=G(11,2)*CP2+G(1,11)*SP2                                  1-00285
C3=G(11,3)*CP3+G(2,11)*SP3                                  1-00286
C4=G(11,4)*CP4+G(3,11)*SP4                                  1-00287
C5=G(11,5)*CP5+G(4,11)*SP5                                  1-00288
C6=G(11,6)*CP6+G(5,11)*SP6                                  1-00289
C7=G(11,7)*CP7+G(6,11)*SP7                                  1-00290
C8=G(11,8)*CP8+G(7,11)*SP8                                  1-00291
C9=G(11,9)*CP9+G(8,11)*SP9                                  1-00292
C10=G(11,10)*CP10+G(9,11)*SP10                              1-00293
C11=G(11,11)*CP11+G(10,11)*SP11                             1-00294
AR=ACR*AR                                                    1-00295
BR=BR-FN(11)*AR*(G(11,1)*P111+C2*P112+C3*P113+C4*P114+C5*P115+C6*P1-00296
+116+C7*P117+C8*P118+C9*P119+C10*P1110+C11*P1111)        1-00297
BT=BT+AR*(G(11,1)*DP111+C2*DP112+C3*DP113+C4*DP114+C5*DP115+C6*DP11-00298
+16+C7*DP117+C8*DP118+C9*DP119+C10*DP1110+C11*DP1111)    1-00299
BP=BP-AR*(FM(2)*(G(11,2)*SP2-G(1,11)*CP2)*P112+FM(3)*(G(11,3)*SP3-1-00300
+G(2,11)*CP3)*P113+FM(4)*(G(11,4)*SP4-G(3,11)*CP4)*P114+FM(5)*(G(111-00301
+,5)*SP5-G(4,11)*CP5)*P115+FM(6)*(G(11,6)*SP6-G(5,11)*CP6)*P116+FM(1-00302
+7)*(G(11,7)*SP7-G(6,11)*CP7)*P117+FM(8)*(G(11,8)*SP8-G(7,11)*CP8)*1-00303
+P118+FM(9)*(G(11,9)*SP9-G(8,11)*CP9)*P119+FM(10)*(G(11,10)*SP10-G(1-00304
+9,11)*CP10)*P1110+FM(11)*(G(11,11)*SP11-G(10,11)*CP11)*P1111) 1-00305
BP=BP/ST

```

	IF (NMAX.LE.11) RETURN	1-00306
	WRITE (*,2) NMAX	1-00476
	RETURN	1-00477
C		
2	FORMAT(57H0 ERROR, THIS MODEL ONLY FOR NMAX=<11, CALL WAS FOR NMAX	
	*, I5)	
C	MAKE A SMOOTH FIT BETWEEN TRUNCATED TERMS.	
10	CON= (R-CONA(N)) / (CONA(N-1) -CONA(N) )	
11	BR=BR+ (XR-BR) *CON	
	BT=BT+ (XT-BT) *CON	
	BP= (BP+ (XP-BP) *CON) /ST	
	RETURN	
20	CON= (R-CONA(N)) / (CONA(N-1) -CONA(N) )	
21	BR=XR+ (BR-XR) *CON	
	BT=XT+ (BT-XT) *CON	
	BP= (XP+ (BP-XP) *CON) /ST	
	RETURN	
	END	1-00480
C		

```

      SUBROUTINE FLDCOF (YEAR,DIMO,NMAXI)
C-----
C  DETERMINES COEFFICIENTS AND DIPOL MOMENT FROM IGRF MODELS
C
C  INPUT:  YEAR      DECIMAL YEAR FOR WHICH GEOMAGNETIC FIELD IS TO
C              BE CALCULATED
C  OUTPUT: DIMO      GEOMAGNETIC DIPOL MOMENT IN GAUSS (NORMALIZED
C              TO EARTH'S RADIUS) AT THE TIME (YEAR)
C  THIS ROUTINE WAS INITIALLY WRITTEN BY
C  D. BILITZA, NSSDC, GSFC, CODE 633, GREENBELT, MD 20771,
C  (301)286-9536  NOV 1987.
C  MODIFIED BY K. A. PFITZER MDSSC TO WORK WITH GAUSS NORMALIZED COEFF.
C-----
      CHARACTER*11      FILMOD, FIL1, FIL2
      DIMENSION      GH1(11,11), GH2(11,11),
1      DTEMOD(10),FILMOD(10)
      DOUBLE PRECISION      X,F0,F
      COMMON/MODEL/      G(11,11)
      COMMON/GENER/      UMR,ERAD,AQUAD,BQUAD
      DATA      FILMOD /'dgrf45.dat', 'dgrf50.dat',
1      'dgrf55.dat', 'dgrf60.dat', 'dgrf65.dat',
2      'dgrf70.dat', 'dgrf75.dat', 'dgrf80.dat',
3      'igrf85.dat', 'igrf85s.dat'/
      DATA      DTEMOD / 1945., 1950., 1955., 1960.,
1      1965., 1970., 1975., 1980., 1985., 1990./
      DATA      LOLD/0/
C
      IU = 11
C-- DETERMINE IGRF-YEARS FOR INPUT-YEAR
      TIME = YEAR
      IYEA = INT(YEAR/5.)*5
      L = (IYEA - 1945)/5 + 1
C
      IF (L.NE.LOLD) THEN
        LOLD=L
        IF (L.LT.1) L=1
        IF (L.GT.9) L=9
        DTE1 = DTEMOD(L)
        FIL1 = FILMOD(L)
        DTE2 = DTEMOD(L+1)
        FIL2 = FILMOD(L+1)
C-- GET IGRF COEFFICIENTS FOR THE BOUNDARY YEARS
        CALL GETGAU (IU, FIL1, NMAX1, ERAD, GH1, IER)
        IF (IER.NE. 0) THEN
          WRITE (*,101) IU,FIL1,NMAX1,ERAD,IER
101      FORMAT (//'      Error in subroutine FELDCOF'/
1      ' IU, FIL1, NMAX1, ERAD, IER: '/
2      I10,A11,I10,1PE12.3,I10)
          STOP
        ENDIF
        CALL GETGAU (IU, FIL2, NMAX2, ERAD, GH2, IER)
        IF (IER.NE. 0) THEN
          WRITE (*,102) IU,FIL2,NMAX2,ERAD,IER
102      FORMAT (//'      Error in subroutine FELDCOF'/
1      ' IU, FIL2, NMAX2, ERAD, IER: '/
2      I10,A11,I10,1PE12.3,I10)
          STOP
        ENDIF
      ENDIF
C-- DETERMINE IGRF COEFFICIENTS FOR YEAR
      IF (L.LE. 9) THEN
        CALL CINTPF (YEAR, DTE1, NMAX1, GH1, DTE2,
1      NMAX2, GH2, NMAXI, G)
      ELSE

```

```

        CALL EXTRAP (YEAR, DTE1, NMAX1, GH1, NMAX2,
1      GH2, NMAX1, G)
      ENDIF
C-- DETERMINE MAGNETIC DIPOL MOMENT
      F0=G(2,1)**2+G(2,2)**2+G(1,2)**2
      DIMO=SQRT(F0)
      RETURN
      END

```

SUBROUTINE GETGAU (IU, FSPEC, NMAX, ERAD, G, IER)

```

C =====
C
C Reads spherical harmonic coefficients from the specified
C file into an array and converts the coefficients to Gauss
C normalized coefficients.
C
C Input:
C   IU      - Logical unit number
C   FSPEC   - File specification
C
C Output:
C   NMAX    - Maximum degree and order of model
C   ERAD    - Earth's radius associated with the spherical
C             harmonic coefficients, in the same units as
C             elevation
C   GH      - Gauss quasi-normal internal spherical
C             harmonic coefficients
C   IER     - Error number: = 0, no error
C               = -2, records out of order
C               = FORTRAN run-time error number
C =====
C
C   CHARACTER  FSPEC*(*)
C   DIMENSION  G(11,11)
C
C -----
C   Open coefficient file. Read past first header record.
C   Read degree and order of model and Earth's radius.
C -----
C   OPEN (IU, FILE=FSPEC, STATUS='OLD', IOSTAT=IER, ERR=999)
C   1   READONLY)
C
C   DO 10 I=1,11
C   DO 10 J=1,11
10  G(I,J)=0.
C
C   READ (IU, *, IOSTAT=IER, ERR=999)
C   READ (IU, *, IOSTAT=IER, ERR=999) MAXN, ERAD
C
C   IF (MAXN.GT.10) MAXN=10
C   DO 30 NN=1,MAXN
C   DO 20 MM=0,NN
C   READ (IU, *, IOSTAT=IER, ERR=999) LN, LM, GNM, HNM
C   IF (NN.NE.LN.OR.MM.NE.LM) THEN
C     IER=-2
C     GOTO 999
C   ENDIF
C
C   N=LN+1
C   M=LM+1
C   G(N,M)=GNM
C   IF (LM.EQ.0) goto 20
C   G(LM,N)=HNM
20  CONTINUE
30  CONTINUE
C   NMAX=MAXN+1
C
C   Invert to Gauss normalized
C   DO 55 N=1,NMAX
C   DO 55 M=1,NMAX
C   CALL CONVPT (N,M,N,M,1)

```

55 CONTINUE  
999 CLOSE (IU)  
RETURN  
END

```

SUBROUTINE CONVRT(G,I,L,K)
DIMENSION S(11,11)
LOGICAL NEXT
DATA NEXT/.FALSE./
IF (NEXT) GOTO 2
NEXT=.TRUE.
S(1,1)=-1.
DO 1 N=2,11
S(N,1)=S(N-1,1)*FLOAT(2*N-3)/FLOAT(N-1)
S(1,N)=0.
J=2
DO 1 M=2,N
S(N,M)=S(N,M-1)*SQRT((FLOAT(N-M+1)*J)/FLOAT(N+M-2))
S(M-1,N)=S(N,M)
1 J=1
2 IF(K.GT.1) GOTO 3
G=G*S(I,L)
RETURN
3 G=G/S(I,L)
RETURN
END
C
C

```

```

SUBROUTINE CINTRP (DATE, DTE1, NMAX1, GH1, DTE2,
1 NMAX2, GH2, NMAX, GH)

```

```

C =====
C
C   Interpolates linearly, in time, between two spherical
C   harmonic models.
C
C   Input:
C       DATE      - Date of resulting model (in decimal year)
C       DTE1      - Date of earlier model
C       NMAX1     - Maximum degree and order of earlier model
C       GH1       - Gauss quasi-normal internal spherical
C                   harmonic coefficients of earlier model
C       DTE2      - Date of later model
C       NMAX2     - Maximum degree and order of later model
C       GH2       - Gauss quasi-normal internal spherical
C                   harmonic coefficients of later model
C
C   Output:
C       GH        - Coefficients of resulting model
C       NMAX      - Maximum degree and order of resulting model
C
C =====
C
C   DIMENSION    GH1(11,11), GH2(11,11), GH(11,11)
C
C   NMAX=MAX0(NMAX1,NMAX2)
C   FACTOR=(DATE-DTE1)/(DTE2-DTE1)
C   DO 234 J= 1,11
C   DO 234 I = 1, 11
234  GH(I,J) = GH1(I,J) + FACTOR * (GH2(I,J) - GH1(I,J))
C
C   RETURN
C   END
C
C

```

```

      SUBROUTINE EXTRAP (DATE, DTE1, NMAX1, GH1, NMAX2,
1      GH2, NMAX, GH)
C =====
C
C   Extrapolates linearly a spherical harmonic model with a
C   rate-of-change model.
C
C   Input:
C       DATE      - Date of resulting model (in decimal year)
C       DTE1      - Date of base model
C       NMAX1     - Maximum degree and order of base model
C       GH1       - Gauss quasi-normal internal spherical
C                  harmonic coefficients of base model
C       NMAX2     - Maximum degree and order of rate-of-change
C                  model
C       GH2       - Gauss quasi-normal internal spherical
C                  harmonic coefficients of rate-of-change model
C
C   Output:
C       GH        - Coefficients of resulting model
C       NMAX      - Maximum degree and order of resulting model
C =====
C
      DIMENSION  GH1(11,11), GH2(11,11), GH(11,11)
C
      NMAX=MAX0(NMAX1,NMAX2)
      FACTOR = (DATE - DTE1)
C
      DO 567 J=1,11
      DO 567 I = 1,11
567  GH(I,J) = GH1(I,J) + FACTOR * GH2(I,J)
C
      RETURN
      END

```

## dgrf45

10 6371.2 1945.0

1 0	-30594.	0.
1 1	-2285.	5810.
2 0	-1244.	0.
2 1	2990.	-1702.
2 2	1578.	477.
3 0	1282.	0.
3 1	-1834.	-499.
3 2	1255.	186.
3 3	913.	-11.
4 0	944.	0.
4 1	776.	144.
4 2	544.	-276.
4 3	-421.	-55.
4 4	304.	-178.
5 0	-253.	0.
5 1	346.	-12.
5 2	194.	95.
5 3	-20.	-67.
5 4	-142.	-119.
5 5	-82.	82.
6 0	59.	0.
6 1	57.	6.
6 2	6.	100.
6 3	-246.	16.
6 4	-25.	-9.
6 5	21.	-16.
6 6	-104.	-39.
7 0	70.	0.
7 1	-40.	-45.
7 2	0.	-18.
7 3	0.	2.
7 4	-29.	6.
7 5	-10.	28.
7 6	15.	-17.
7 7	29.	-22.
8 0	13.	0.
8 1	7.	12.
8 2	-8.	-21.
8 3	-5.	-12.
8 4	9.	-7.
8 5	7.	2.
8 6	-10.	18.
8 7	7.	3.
8 8	2.	-11.
9 0	5.	0.
9 1	-21.	-27.
9 2	1.	17.
9 3	-11.	29.
9 4	3.	-9.
9 5	16.	4.
9 6	-3.	9.
9 7	-4.	6.
9 8	-3.	1.
9 9	-4.	8.
10 0	-3.	0.
10 1	11.	5.
10 2	1.	1.
10 3	2.	-20.
10 4	-5.	-1.
10 5	-1.	-6.
10 6	8.	6.
10 7	-1.	-4.
10 8	-3.	-2.
10 9	5.	0.
10 10	-2.	-2.

## dgrf50

10 6371.2 1950.0

1 0	-30554.	0.
1 1	-2250.	5815.
2 0	-1341.	0.
2 1	2998.	-1810.
2 2	1576.	381.
3 0	1297.	0.
3 1	-1889.	-476.
3 2	1274.	206.
3 3	896.	-46.
4 0	954.	0.
4 1	792.	136.
4 2	528.	-278.
4 3	-408.	-37.
4 4	303.	-210.
5 0	-240.	0.
5 1	349.	3.
5 2	211.	103.
5 3	-20.	-87.
5 4	-147.	-122.
5 5	-76.	80.
6 0	54.	0.
6 1	57.	-1.
6 2	4.	99.
6 3	-247.	33.
6 4	-16.	-12.
6 5	12.	-12.
6 6	-105.	-30.
7 0	65.	0.
7 1	-55.	-35.
7 2	2.	-17.
7 3	1.	0.
7 4	-40.	10.
7 5	-7.	36.
7 6	5.	-18.
7 7	19.	-16.
8 0	22.	0.
8 1	15.	5.
8 2	-4.	-22.
8 3	-1.	0.
8 4	11.	-21.
8 5	15.	-8.
8 6	-13.	17.
8 7	5.	-4.
8 8	-1.	-17.
9 0	3.	0.
9 1	-7.	-24.
9 2	-1.	19.
9 3	-25.	12.
9 4	10.	2.
9 5	5.	2.
9 6	-5.	8.
9 7	-2.	8.
9 8	3.	-11.
9 9	8.	-7.
10 0	-8.	0.
10 1	4.	13.
10 2	-1.	-2.
10 3	13.	-10.
10 4	-4.	2.
10 5	4.	-3.
10 6	12.	6.
10 7	3.	-3.
10 8	2.	6.
10 9	10.	11.
10 10	3.	8.

## dgrf55

10 6371.2 1955.0

1 0	-30500.	0.
1 1	-2215.	5820.
2 0	-1440.	0.
2 1	3003.	-1898.
2 2	1581.	291.
3 0	1302.	0.
3 1	-1944.	-462.
3 2	1288.	216.
3 3	882.	-83.
4 0	958.	0.
4 1	796.	133.
4 2	510.	-274.
4 3	-397.	-23.
4 4	290.	-230.
5 0	-229.	0.
5 1	360.	15.
5 2	230.	110.
5 3	-23.	-98.
5 4	-152.	-121.
5 5	-69.	78.
6 0	47.	0.
6 1	57.	-9.
6 2	3.	96.
6 3	-247.	48.
6 4	-8.	-16.
6 5	7.	-12.
6 6	-107.	-24.
7 0	65.	0.
7 1	-56.	-50.
7 2	2.	-24.
7 3	10.	-4.
7 4	-32.	8.
7 5	-11.	28.
7 6	9.	-20.
7 7	18.	-18.
8 0	11.	0.
8 1	9.	10.
8 2	-6.	-15.
8 3	-14.	5.
8 4	6.	-23.
8 5	10.	3.
8 6	-7.	23.
8 7	6.	-4.
8 8	9.	-13.
9 0	4.	0.
9 1	9.	-11.
9 2	-4.	12.
9 3	-5.	7.
9 4	2.	6.
9 5	4.	-2.
9 6	1.	10.
9 7	2.	7.
9 8	2.	-6.
9 9	5.	5.
10 0	-3.	0.
10 1	-5.	-4.
10 2	-1.	0.
10 3	2.	-8.
10 4	-3.	-2.
10 5	7.	-4.
10 6	4.	1.
10 7	-2.	-3.
10 8	6.	7.
10 9	-2.	-1.
10 10	0.	-3.

## dgrf60

10 6371.2 1960.0

1 0	-30421.	0.
1 1	-2169.	5776.
2 0	-1555.	0.
2 1	3002.	-2016.
2 2	1590.	114.
3 0	1302.	0.
3 1	-1992.	-404.
3 2	1289.	240.
3 3	878.	-165.
4 0	957.	0.
4 1	800.	148.
4 2	504.	-269.
4 3	-394.	13.
4 4	269.	-269.
5 0	-222.	0.
5 1	362.	19.
5 2	242.	128.
5 3	-26.	-31.
5 4	-156.	-97.
5 5	-63.	81.
6 0	46.	0.
6 1	58.	-11.
6 2	1.	100.
6 3	-237.	68.
6 4	-1.	-32.
6 5	-2.	-8.
6 6	-113.	-7.
7 0	67.	0.
7 1	-56.	-61.
7 2	5.	-27.
7 3	15.	-2.
7 4	-32.	6.
7 5	-7.	26.
7 6	17.	-23.
7 7	8.	-12.
8 0	15.	0.
8 1	6.	7.
8 2	-4.	-12.
8 3	-11.	9.
8 4	2.	-16.
8 5	10.	4.
8 6	-5.	24.
8 7	10.	-3.
8 8	8.	-17.
9 0	4.	0.
9 1	6.	-22.
9 2	0.	15.
9 3	-9.	7.
9 4	1.	-4.
9 5	4.	-5.
9 6	-1.	10.
9 7	-2.	10.
9 8	3.	-4.
9 9	-1.	1.
10 0	1.	0.
10 1	-3.	2.
10 2	4.	1.
10 3	0.	2.
10 4	-1.	6.
10 5	4.	-4.
10 6	6.	0.
10 7	1.	-1.
10 8	-1.	3.
10 9	2.	3.
10 10	0.	-4.

## dgrf65

10 6371.2 1965.0

1 0	-30334.	0.
1 1	-2119.	5776.
2 0	-1662.	0.
2 1	2997.	-2016.
2 2	1594.	114.
3 0	1297.	0.
3 1	-2038.	-404.
3 2	1292.	240.
3 3	856.	-165.
4 0	957.	0.
4 1	804.	148.
4 2	479.	-269.
4 3	-390.	13.
4 4	252.	-269.
5 0	-219.	0.
5 1	358.	19.
5 2	254.	128.
5 3	-31.	-126.
5 4	-157.	-97.
5 5	-62.	81.
6 0	45.	0.
6 1	61.	-11.
6 2	8.	100.
6 3	-228.	68.
6 4	4.	-32.
6 5	1.	-8.
6 6	-111.	-7.
7 0	75.	0.
7 1	-57.	-61.
7 2	4.	-27.
7 3	13.	-2.
7 4	-26.	6.
7 5	-6.	26.
7 6	13.	-23.
7 7	1.	-12.
8 0	13.	0.
8 1	5.	7.
8 2	-4.	-12.
8 3	-14.	9.
8 4	0.	-16.
8 5	8.	4.
8 6	-1.	24.
8 7	11.	-3.
8 8	4.	-17.
9 0	8.	0.
9 1	10.	-22.
9 2	2.	15.
9 3	-13.	7.
9 4	10.	-4.
9 5	-1.	-5.
9 6	-1.	10.
9 7	5.	10.
9 8	1.	-4.
9 9	-2.	1.
10 0	-2.	0.
10 1	-3.	2.
10 2	2.	1.
10 3	-5.	2.
10 4	-2.	6.
10 5	4.	-4.
10 6	4.	0.
10 7	0.	-2.
10 8	2.	3.
10 9	2.	0.
10 10	0.	-6.

## dgrf70

10 6371.2 1970.0

1 0	-30220.	0.
1 1	-2068.	5737.
2 0	-1781.	0.
2 1	3000.	-2047.
2 2	1611.	25.
3 0	1287.	0.
3 1	-2091.	-366.
3 2	1278.	251.
3 3	838.	-196.
4 0	952.	0.
4 1	800.	167.
4 2	461.	-266.
4 3	-395.	26.
4 4	234.	-279.
5 0	-216.	0.
5 1	359.	26.
5 2	262.	139.
5 3	-42.	-139.
5 4	-160.	-91.
5 5	-56.	83.
6 0	43.	0.
6 1	64.	-12.
6 2	15.	100.
6 3	-212.	72.
6 4	2.	-37.
6 5	3.	-6.
6 6	-112.	1.
7 0	72.	0.
7 1	-57.	-70.
7 2	1.	-27.
7 3	14.	-4.
7 4	-22.	8.
7 5	-2.	23.
7 6	13.	-23.
7 7	-2.	-11.
8 0	14.	0.
8 1	6.	7.
8 2	-2.	-15.
8 3	-13.	6.
8 4	-3.	-17.
8 5	5.	6.
8 6	0.	21.
8 7	11.	-6.
8 8	3.	-16.
9 0	8.	0.
9 1	10.	-21.
9 2	2.	16.
9 3	-12.	6.
9 4	10.	-4.
9 5	-1.	-5.
9 6	0.	10.
9 7	3.	11.
9 8	1.	-2.
9 9	-1.	1.
10 0	-3.	0.
10 1	-3.	1.
10 2	2.	1.
10 3	-5.	3.
10 4	-1.	4.
10 5	6.	-4.
10 6	4.	0.
10 7	1.	-1.
10 8	0.	3.
10 9	3.	1.
10 10	-1.	-4.

## dgrf75

10 6371.2 1975.0

1 0	-30100.	0.
1 1	-2013.	5675.
2 0	-1902.	0.
2 1	3010.	-2067.
2 2	1632.	-68.
3 0	1276.	0.
3 1	-2144.	-333.
3 2	1260.	262.
3 3	830.	-223.
4 0	946.	0.
4 1	791.	191.
4 2	438.	-265.
4 3	-405.	39.
4 4	216.	-288.
5 0	-218.	0.
5 1	356.	31.
5 2	264.	148.
5 3	-59.	-152.
5 4	-159.	-83.
5 5	-49.	88.
6 0	45.	0.
6 1	66.	-13.
6 2	28.	99.
6 3	-198.	75.
6 4	1.	-41.
6 5	6.	-4.
6 6	-111.	11.
7 0	71.	0.
7 1	-56.	-77.
7 2	1.	-26.
7 3	16.	-5.
7 4	-14.	10.
7 5	0.	22.
7 6	12.	-23.
7 7	-5.	-12.
8 0	14.	0.
8 1	6.	6.
8 2	-1.	-16.
8 3	-12.	4.
8 4	-8.	-19.
8 5	4.	6.
8 6	0.	18.
8 7	10.	-10.
8 8	1.	-17.
9 0	7.	0.
9 1	10.	-21.
9 2	2.	16.
9 3	-12.	7.
9 4	10.	-4.
9 5	-1.	-5.
9 6	-1.	10.
9 7	4.	11.
9 8	1.	-3.
9 9	-2.	1.
10 0	-3.	0.
10 1	-3.	1.
10 2	2.	1.
10 3	-5.	3.
10 4	-2.	4.
10 5	5.	-4.
10 6	4.	-1.
10 7	1.	-1.
10 8	0.	3.
10 9	3.	1.
10 10	-1.	-5.

## dgrf80

10 6371.2 1980.0

1 0	-29992.	0.
1 1	-1956.	5604.
2 0	-1997.	0.
2 1	3027.	-2129.
2 2	1663.	-200.
3 0	1281.	0.
3 1	-2180.	-336.
3 2	1251.	271.
3 3	833.	-252.
4 0	938.	0.
4 1	782.	212.
4 2	398.	-257.
4 3	-419.	53.
4 4	199.	-297.
5 0	-218.	0.
5 1	357.	46.
5 2	261.	150.
5 3	-74.	-151.
5 4	-162.	-78.
5 5	-48.	92.
6 0	48.	0.
6 1	66.	-15.
6 2	42.	93.
6 3	-192.	71.
6 4	4.	-43.
6 5	14.	-2.
6 6	-108.	17.
7 0	72.	0.
7 1	-59.	-82.
7 2	2.	-27.
7 3	21.	-5.
7 4	-12.	16.
7 5	1.	18.
7 6	11.	-23.
7 7	-2.	-10.
8 0	18.	0.
8 1	6.	7.
8 2	0.	-18.
8 3	-11.	4.
8 4	-7.	-22.
8 5	4.	9.
8 6	3.	16.
8 7	6.	-13.
8 8	-1.	-15.
9 0	5.	0.
9 1	10.	-21.
9 2	1.	16.
9 3	-12.	9.
9 4	9.	-5.
9 5	-3.	-6.
9 6	-1.	9.
9 7	7.	10.
9 8	2.	-6.
9 9	-5.	2.
10 0	-4.	0.
10 1	-4.	1.
10 2	2.	0.
10 3	-5.	3.
10 4	-2.	6.
10 5	5.	-4.
10 6	3.	0.
10 7	1.	-1.
10 8	2.	4.
10 9	3.	0.
10 10	0.	-6.

## igrf85

10 6371.2 1985.0

1 0	-29877.	0.
1 1	-1903.	5497.
2 0	-2073.	0.
2 1	3045.	-2191.
2 2	1691.	-309.
3 0	1300.	0.
3 1	-2208.	-312.
3 2	1244.	284.
3 3	835.	-296.
4 0	937.	0.
4 1	780.	233.
4 2	363.	-250.
4 3	-426.	68.
4 4	169.	-298.
5 0	-215.	0.
5 1	356.	47.
5 2	253.	148.
5 3	-94.	-155.
5 4	-161.	-75.
5 5	-48.	95.
6 0	52.	0.
6 1	65.	-16.
6 2	50.	90.
6 3	-186.	69.
6 4	4.	-50.
6 5	17.	-4.
6 6	-102.	20.
7 0	75.	0.
7 1	-61.	-82.
7 2	2.	-26.
7 3	24.	-1.
7 4	-6.	23.
7 5	4.	17.
7 6	9.	-21.
7 7	0.	-6.
8 0	21.	0.
8 1	6.	7.
8 2	0.	-21.
8 3	-11.	5.
8 4	-9.	-25.
8 5	2.	11.
8 6	4.	12.
8 7	4.	-6.
8 8	-6.	-10.
9 0	5.	0.
9 1	10.	-21.
9 2	1.	16.
9 3	-12.	9.
9 4	9.	-5.
9 5	-3.	-6.
9 6	-1.	9.
9 7	7.	10.
9 8	2.	-6.
9 9	-5.	2.
10 0	-4.	0.
10 1	-4.	1.
10 2	2.	0.
10 3	-5.	3.
10 4	-2.	6.
10 5	5.	-4.
10 6	3.	0.
10 7	1.	-1.
10 8	2.	4.
10 9	3.	0.
10 10	0.	-6.

igrf85s

8 1.7 1990.0

1	1	23.2	1.0
1	1	10.0	-0.10
2	1	-13.1	1.1
2	1	1.4	-0.10
2	2	1.0	1.1
3	1	0.1	1.1
3	1	-0.6	1.1
3	2	-0.1	1.1
3	3	1.1	-0.10
4	1	0.1	1.0
4	1	-0.6	1.4
4	2	-0.4	1.1
4	3	-0.4	1.1
4	4	-0.8	1.1
5	1	1.3	1.1
5	1	1.1	1.1
5	2	-0.5	1.1
5	3	-0.2	-0.1
5	4	0.1	0.6
5	5	-0.1	1.0
5	6	1.4	0.0
5	7	-0.3	-0.4
5	8	1.7	-0.1
5	9	0.6	-0.0
5	10	1.0	-0.0
5	11	1.3	-0.0
5	12	1.0	-0.1
6	1	0.2	1.1
6	2	-0.4	1.0
6	3	-0.1	1.1
6	4	0.8	1.1
6	5	1.0	1.4
6	6	0.4	0.0
6	7	-0.5	0.2
6	8	-0.1	1.1
6	9	0.1	1.0
6	10	0.0	1.1
6	11	0.3	0.0
6	12	0.4	1.1
7	1	-0.5	-0.1
7	2	-0.3	1.1
7	3	0.1	-0.1
7	4	-0.3	-0.1

## **Appendix B**

### **External Magnetic Field Routines**

These listings are the 1977 Olson-Pfitzer tilt dependent routine including the routine that combines the internal and the external field. These routines are included here for completeness. They were not developed or changed as a part of this effort. They are, however, necessary in order for the remaining software to function properly.

```

C      BMNIGRF -- A TEST ROUTINE TO CHECK THE OPERATION OF THE TILT
C      DEPENDENT MODEL AND IT COMBINATION WITH THE IGRF MAIN FIELD
C
C      DIMENSION X(3),B(3)
C      COMMON/BXYZCM/YEAR,DAYYR,UT,KODE,JSW
C
C      SET UP THE YEAR FOR THE MAIN FIELD ROUTINE
C
C      YEAR=1985.
C
C      SET THE SWITCH TO USE EXTERNAL PLUS INTERNAL FIELD
C
C      JSW=1
C
C      SET THE SWITCH TO USE INPUT AND OUTPUT IN CARTESIAN COORDS
C
C      KODE=1
C
C      SET UP A CARTESIAN COORDINATE TEST LOOP
C
C      SET UP DATE AND TIME
C      DO 200 ID=1,2
C      DAYYR=90*ID
C      DO 190 IUT=1,3
C      UT=IUT*6-6
C
C      PRINT PAGE HEADER
C      WRITE (6,110)
110    FORMAT(77H1DAYOFYR   UT           X           Y           Z           BX           BY
C      *           BZ           BMAG,/)
C      SET UP POSITION IN CARTESIAN COORDS
C      DO 180 IZ=1,3
C      X(3)=3*IZ-6
C      DO 170 IY=1,3
C      X(2)=3*IY-6
C      DO 160 IX=1,6
C      X(1)=4*IX-14
C
C      GET THE MAGNETIC FIELD VALUES
C      CALL BMNEXT(X,B,BMAG)
C      WRITE (6,120) DAYYR,UT,X,B,BMAG
120    FORMAT(F6.0,4F8.2,4F10.5)
160    CONTINUE
170    CONTINUE
180    CONTINUE
190    CONTINUE
200    CONTINUE
C
C      SET UP FOR SPHERICAL COORDINATES
C
C      1000      KODE=2
C
C      SET DATE AND TIME
C      DO 300 ID=1,2
C      DAYYR=90*ID
C      DO 290 IUT=1,3
C      UT=IUT*6-6
C
C      PRINT PAGE HEADER
C      WRITE (6,210)
210    FORMAT(77H1DAYOFYR   UT           R           THETA       PHI           BR           BTHE
C      *TA           BPHI           BMAG,/)
C

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```

C      SET UP POSITIONS IN SPHERICAL COORDS
      DO 280 IR=1,3
      X(1)=IR*3
      DO 270 IT=1,3
      X(2)=IT*45
      DO 260 IP=1,6
      X(3)=(IP-1)*60

C
C      GET THE MAGNETIC FIELD
      CALL BMNEXT(X,B,BMAG)
      WRITE(6,120) DAYYR,UT,X,B,BMAG
260    CONTINUE
270    CONTINUE
280    CONTINUE
290    CONTINUE
300    CONTINUE
      END

```

SUBROUTINE BMNEXT (XX,B,BMAG)

PURPOSE

TO DETERMINE THE MAIN MAGNETIC FIELD PLUS THE EXTERNAL  
FIELD

METHOD

DETERMINES THE VECTOR MAGNETIC FIELD IN GEOGRAPHIC  
COORDINATES USING A SPHERICAL COORDINATE EXPANSION OF THE  
EARTHS INTERNAL FIELD AND A CARTESIAN COORDINATE EXPANSION  
OF THE BOUNDARY, TAIL AND RING CURRENT FIELDS IN SOLAR  
MAGNETIC COORDINATES

INPUT -- ARGUMENT LIST

XX A REAL ARRAY CONTAINING THE POSITION IN GEOGRAPHIC  
COORDINATES  
IF KODE = 1  
XX(1)=X, XX(2)=Y, XX(3)=Z, WHERE X, Y, Z ARE IN EARTH  
RADII. THE DIRECTION OF Z IS ALONG THE EARTHS ROTATION  
AXIS TOWARDS THE GEOGRAPHIC NORTH POLE. THE DIRECTION  
OF X IS TO THE GREENWICH MERIDIAN IN THE EQUATORIAL  
PLANE. THE Y AXIS IS IN THE EQUATORIAL PLANE NORMAL  
TO X AND Z IN A RIGHT HANDED SENSE.  
IF KODE = 2  
XX(1)=R, GEOCENTRIC RADIUS IN EARTH RADII,  
XX(2)=THETAG, COLATITUDE IN DEGREES,  
XX(3)=PHIG, LONGITUDE IN DEGREES

INPUT -- COMMON BLOCK BXYZCM

UT THE CURRENT UNIVERSAL TIME IN HOURS  
KODE A FLOW CONTROL VARIABLE. KODE EQUAL TO ONE MEANS THAT  
INPUT AND OUTPUT ARE IN CARTESIAN COORDINATES. KODE  
EQUAL TO TWO MEANS THAT INPUT AND OUTPUT ARE SPHERICAL  
COORDINATES.  
DAYYR THE NUMBER OF THE DAY OF YEAR  
JSW A FLOW CONTROL VARIABLE. IF JSW IS LESS THAN ZERO, THE  
THE FIELD IS COMPUTED USING THE INTERNAL FIELD ONLY.  
IF JSW IS GREATER THAN OR EQUAL TO ZERO THE FIELD  
WILL BE COMPUTED USING THE INTERNAL PLUS EXTERNAL  
FIELD.  
YEAR THE YEAR USED BY THE INTERNAL MAGNETIC FIELD ROUTINE  
TO TAKE INTO ACCOUNT THE SECULAR VARIATIONS  
(E.G. JULY 15, 1964 = 1964.54)  
NOTE\*\*\*\* YEAR SHOULD BE CHANGED ONLY EVERY FEW DAYS OR  
MONTHS. NEW FIELD COEFFICIENTS MUST BE COMPUTED FOR  
EVERY CHANGE IN YEAR. THIS COULD CAUSE A LARGE INCREASE  
IN COMPUTER TIME. THE EARTHS FIELD CHANGES ONLY ABOUT  
.001 GAUSS/YEAR AT THE EARTHS SURFACE.

OUTPUT -- ARGUMENT LIST

B A REAL ARRAY CONTAINING THE COMPONENTS OF THE MAGNETIC  
FIELD IN GAUSS AT THE CURRENT POSITION AND TIME  
IF KODE = 1  
B(1)=BX, B(2)=BY, B(3)=BZ THE CARTESIAN COMPONENTS  
OF THE MAGNETIC FIELD IN GEOGRAPHIC COORDINATES  
IF KODE = 2  
B(1)=BR, RADIAL COMPONENT OF THE FIELD, POSITIVE IN THE  
DIRECTION OF INCREASING RADIUS.  
B(2)=BTHETA, COMPONENT IN LATITUDE, POSITIVE IN THE  
DIRECTION OF INCREASING COLATITUDE  
B(3)=BPHI, COMPONENT IN LONGITUDE, POSITIVE IN THE  
DIRECTION OF INCREASING LONGITUDE.  
BMAG THE MAGNITUDE OF THE MAGNETIC FIELD VECTOR IN UNITS OF  
GAUSS.

```

C
C OUTPUT -- COMMON BLOCK BXYZCM
C   XMLAT THE MAGNETIC LATITUDE AT THE CURRENT POSITION IN RADIANS
C
C SUBROUTINE CONSTANTS
C   PICON THE NUMBER OF DEGREES PER RADIAN
C   SIN D THE SINE OF THE COLATITUDE OF THE DIPOLE AXIS
C   COS D THE COSINE OF THE COLATITUDE OF THE DIPOLE AXIS
C   C69 COSINE OF 69
C   S69 SINE OF 69
C
C CALLING SUBROUTINES
C   SUBROUTINE INVARM
C
C SUBROUTINES REQUIRED
C   SUBROUTINE BYYZMU
C   SUBROUTINE ANGLE
C   SUBROUTINE SPIGRF
C
C VARIABLES
C   AOR INVERSE OF RADIUS VECTOR (AOR=1./R)
C   BGMX,BGMY,BGMZ INTERMEDIATE VALUES OF THE MAGNETIC FIELD
C   VECTOR DURING COORDINATE TRANSFORMATION
C   BMX,BMY,BMZ EXTERNAL MAGNETIC FIELD IN GEOMAGNETIC COORDINATES
C   BP,BR,BT COMPONENTS OF INTERNAL FIELD IN SPHERICAL COORDINATES
C   BP IS LONGITUDINAL COMPONENT
C   BR IS RADIAL COMPONENT
C   BT IS LATITUDINAL COMPONENT
C   BX,BY,BZ CARTESIAN COMPONENT OF EXTERNAL FIELD IN GEOGRAPHIC
C   COORDINATES
C   CP COSINE OF COLATITUDE
C   CPS COSINE OF HOUR ANGLE TO GET FROM SOLAR MAGNETIC TO
C   GEOMAGNETIC COORDINATES
C   CT COSINE OF GEOGRAPHIC LONGITUDE
C   DAYLST LAST DAY FOR WHICH TILT AND HOUR ANGLE WERE UPDATED
C   NMAX MAXIMUM NUMBER OF TERMS USED BY INTERNAL FIELD ROUTINE
C   SET UP BY INTERNAL FIELD ROUTINE
C   PHIG GEOGRAPHIC COLATITUDE
C   R RADIUS VECTOR TO POSITION POINT
C   R2 R**2
C   SP SINE OF COLATITUDE
C   SPS SINE OF HOUR ANGLE TO GET FROM SOLAR MAGNETIC TO
C   GEOMAGNETIC COORDINATES
C   ST SINE OF LONGITUDE
C   THETAG GEOGRAPHIC LONGITUDE
C   TILT TILT OF THE DIPOLE AXIS
C   UTLST LAST UNIVERSAL TIME FOR WHICH TILT AND HOUR ANGLE WERE
C   UPDATED
C   X A REAL ARRAY HOLDING THE POSITION VECTOR IN SOLAR
C   MAGNETIC COORDINATES
C   XP,YP,ZP POSITION VECTOR IN GEOMAGNETIC COORDINATES
C   XPP,YPP INTERMEDIATE POSITION COMPONENT DURING COORDINATE
C   TRANSFORMATION
C   YEARI TRANSMITS THE YEAR TO THE INTERNAL FIELD ROUTINE
C
C VERSION 10/25/77
C FOR MORE INFORMATION CALL OR WRITE K. A. PFITZER AT MCDONNELL
C DOUGLAS ASTRONAUTICS CO. 5301 BOLSA AVE, HUNTINGTON BEACH CALIF.
C PHONE (714) 896-3231.
C
C DIMENSION X(3),B(3),XX(3)
C COMMON/BXYZCM/YEAR,DAYR,UT,KODE,JSW
C COMMON /GCOM/ ST,CT,SP,CP,AOR,BT,BP,BR,NMAX,YEARI
C DATA PICON/57.29577951/,SIND,COSD/.2027872954,.9792228106/,

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C      *S69,C69/.9335804265,.3583679495/,UTLST,DAYLST/2*123456./
C
C      UPDATE THE ROTATION HOUR ANGLE AND TILT ANGLE IF THE UNIVERSAL
C      TIME OR DAY OF YEAR HAS CHANGED SINCE THE LAST CALL
C
C      IF(UT.EQ.UTLST.AND.DAYR.EQ.DAYLST) GO TO 1
C      UTLST=UT
C      DAYLST=DAYR
C      CALL ANGLE (TILT,SPS,CPS)
1     IF(KODE.GT.1) GO TO 3
C
C      DETERMINE THE SPHERICAL COORDINATES OF POSITION IF CARTESIAN
C      COORDINATES WERE ENTERED
C
C      X(1)=XX(1)
C      X(2)=XX(2)
C      X(3)=XX(3)
C      R2=X(1)**2+X(2)**2
C      R=SQRT(X(3)**2+R2)
C      R2=SQRT(R2)
C      CT=X(3)/R
C      ST=R2/R
C      CP=X(1)/R2
C      SP=X(2)/R2
C      GO TO 5
C
C      DETERMINE THE CARTESIAN COORDINATES OF POSITION IF SPHERICAL
C      COORDINATES WERE ENTERED
C
3     R=XX(1)
C      THETAG=XX(2)/PICON
C      PHIG=XX(3)/PICON
C      CT=COS(THETAG)
C      ST=SIN(THETAG)
C      CP=COS(PHIG)
C      SP=SIN(PHIG)
C      X(1)=R*ST*CP
C      X(2)=R*ST*SP
C      X(3)=R*CT
5     BX=0.
C      BY=0.
C      BZ=0.
C
C      IF THE EXTERNAL MAGNETIC FIELD IS TO BE USED IN THE COMPUTATION,
C      COMPUTE THE SOLAR MAGNETIC COORDINATES
C
C      IF(JSW.LT.0) GO TO 9
C
C      FIRST ROTATION IS ABOUT THE Z-AXIS THROUGH AN ANGLE OF 291 DEGREES
C      (THE LONGITUDE OF THE MAGNETIC NORTH POLE)
C
C      XPP=X(1)*C69-X(2)*S69
C      YPP= X(1)*S69+X(2)*C69
C
C      SECOND ROTATION IS ABOUT THE NEW Y-AXIS THROUGH AN ANGLE OF 11.7
C      DEGREES (THE COLATITUDE OF THE MAGNETIC NORTH POLE)
C
C      ZP=XPP*SIND+X(3)*COSD
C      XP=XPP*COSD-X(3)*SIND
C      YP=YPP
C
C      ROTATION IS ABOUT THE MAGNETIC Z-AXIS THROUGH THE HOUR ANGLE OF
C      THE SUN FROM THE PRIME MAGNETIC MERIDIAN (NEGATIVE ROTATION)
C

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X(1)=XP*CPS-YP*SPS
X(2)=XP*SPS+YP*CPS
X(3)=ZP
C
C DETERMINE THE EXTERNAL MAGNETIC FIELD USING A TILT DEPENDENT
C MAGNETIC FIELD
C
C CALL BXYZMU(X,B,TILT)
C
C THE CARTESIAN COMPONENTS OF THE FIELD ARE IN SOLAR MAGNETIC
C COORDINATES. THE COMPONENTS ARE NEEDED IN THE GEOGRAPHIC
C COORDINATE SYSTEM
C
C FIRST ROTATION IS ABOUT THE MAGNETIC Z-AXIS THROUGH THE HOUR
C ANGLE OF THE SUN TO THE PRIME MAGNETIC MERIDIAN
C (POSITIVE ROTATION) PUTS RESULTS INTO GEOMAGNETIC COORDINATES
C
BMX=B(1)*CPS+B(2)*SPS
BMY=-B(1)*SPS+B(2)*CPS
BMZ=B(3)
C
C SECOND ROTATION IS ABOUT THE MAGNETIC Y-AXIS THOUGH -11.7 DEGREES
C COLATITUDE
C
BGMX=BMX*COSD+BMZ*SIND
BGMY=BMY
BGMZ=-BMX*SIND+BMZ*COSD
C
C THIRD ROTATION IS ABOUT THE NEW Z-AXIS THROUGH -291 DEGREES
C
BX=BGMX*C69+BGMY*S69
BY=-BGMX*S69+BGMY*C69
BZ=BGMZ
C
C DETERMINE THE MAIN FIELD
C
9 CONTINUE
AOR=1./R
YEARI=YEAR
CALL SPIGRF
IF(KODE.GT.1) GO TO 10
C
C IF THE OUTPUT IS TO BE IN CARTESIAN GEOGRAPHIC COORDINATES CONVERT
C THE MAIN MAGNETIC FIELD AND ADD
C
B(1)=(BX+CP*(ST*BR+CT*BT)-SP*BP)*0.00001
B(2)=(BY+SP*(ST*BR+CT*BT)+CP*BP)*0.00001
B(3)=(BZ+CT*BR-ST*BT)*0.00001
GO TO 20
C
C IF OUTPUT IS TO BE IN SPHERICAL GEOGRAPHIC CONVERT THE EXTERNAL
C FIELD AND ADD
C
10 B(1)=(BR+(BX*CP+BY*SP)*ST+BZ*CT)*0.00001
B(2)=(BT+(BX*CP+BY*SP)*CT-BZ*ST)*0.00001
B(3)=(BP+BY*CP-BX*SP)*0.00001
C
C DETERMINE THE MAGNITUDE OF THE FIELD VECTOR
C
20 BMAG=SQRT(B(1)**2+B(2)**2+B(3)**2)
RETURN
END

```

SUBROUTINE ANGLE(TILT,SINPHE,COSPHE)

PURPOSE

THIS ROUTINE CALCULATES THE ANGLE BETWEEN THE MAGNETIC DIPOLE AXIS AND THE SUN-EARTH LINE AS WELL AS THE ROTATION SINES AND COSINES TO CONVERT FROM GEOMAGNETIC TO SOLAR MAGNETIC COORDINATES

METHOD

MAGNETIC COORDINATES HAVE THEIR ORIGIN AT THE CENTER OF THE EARTH WITH THE Z AXIS ALLIGNED THROUGH THE GEOMAGNETIC NORTH POLE. IN GEOMAGNETIC COORDINATES THE X AXIS IS IN THE PLANE PASSING THROUGH THE DIPOLE AXIS AND THE GEOGRAPHIC AXIS (ABOUT 69 DEGREES WEST LONG.). IN SOLAR MAGNETIC COORDINATES X AXIS LIES IN THE PLANE CONTAINING THE SUN EARTH LINE AND THE Z AXIS (POSITIVE X AXIS HAS A LARGE COMPONENT IN THE SOLAR DIRECTION). THE Y AXIS IS ORTHOGONAL TO THE X AND Z AXIS SUCH THAT X, Y AND Z FORM A RIGHT HANDED SYSTEM. THE ECCLIPTIC COORDINATE SYSTEM HAS ITS Z AXIS ALONG THE ECCLIPTIC NORTH POLE (THROUGH THE CENTER OF THE EARTH AND PERPENDICULAR TO THE EARTHS ORBITAL PLANE) THE X AXIS POINTS TOWARD THE SUN AND Y FORMS A RIGHT HANDED COORDINATE SYSTEM. IN THIS ROUTINE IN ORDER TO REDUCE COMPUTER TIME THE APPROXIMATION OF A CIRCULAR EARTH ORBIT AROUND THE SUN IS MADE.

INPUT -- COMMON BLOCK BXYZCM

DAYYR IS THE DAY OF YEAR (1.-366.). IT MUST BE A WHOLE NUMBER. DAY 1 IS JANUARY 1.  
UT THE UNIVERSAL TIME IN HOURS (0.0000-24.00000)

OUTPUT -- PARAMETER LIST

TILT THE TILT OF THE DIPOLE AXIS IN DEGREES.  
TILT = 90. - PSI, WHERE PSI IS THE ANGLE BETWEEN THE MAGNETIC DIPOLE AXIS AND THE SOLAR DIRECTION.  
SINPHE THE SINE OF THE ROTATION ANGLE ABOUT THE MAGNETIC Z AXIS TO CONVERT FROM GEOMAGNETIC TO SOLAR MAGNETIC COORDINATES  
COSPHE THE COSINE OF THE ROTATION ANGLE ABOUT THE MAGNETIC Z AXIS TO CONVERT FROM GEOMAGNETIC TO SOLAR MAGNETIC COORDINATES

CONSTANTS

PI2 PI / 2.  
CON 180. / PI CONVERTS RADIANS TO DEGREES  
SALF SINE (11.7) INCLINATION OF MAGNETIC Z TO GEOGRAPHIC Z  
CALF COSINE (11.7)  
SGAM SIN (23.5) INCLINATION OF ROTATION AXIS TO ECCLIPTIC Z  
CGAM COSINE (23.5)  
SASG SALF \* SGAM  
SACG SALF \* CGAM  
CASG CALF \* SGAM  
CACG CALF \* CGAM  
W EARTHS ANGULAR ROTATION FREQUENCY CORRECTED FOR ITS ONCE A YEAR ROTATION ABOUT THE SUN (UNITS ARE 1/HOURS)

CALLING SUBROUTINES

SUBROUTINE RMNEXT

VARIABLES

WT INSTANTANEOUS ROTATION ANGLE AT THE SPECIFIED UNIVERSAL TIME AND DAY OF YEAR  
CWT WT/365.256  
XX,XY,XZ COMPONENTS OF THE GEOMAGNETIC X AXIS IN ECCLIPTIC

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C          COORDINATES
C          ZX,ZY,ZZ COMPONENTS OF THE DIPOLE AXIS IN ECCLIPITIC COORDINATES
C          OSP,SSMLT,CSMLT,SBWT,CBWT,SMLSWT,SMLCWT,CMLSWT,CMLCWT ARE
C          SINES AND COSINES AND THEIR PRODUCTS AND ARE SET UP
C          TO MINIMIZE COMPUTER TIME
C
C          COMMON/BXYZCM/YEAR, DAYYR, UT, KODE, JSW
C          DATA IFIRST/0/
C
C          THE FIRST TIME TROUGH THE SUBROUTINE SET UP THE FIXED CONSTANTS
C          IF(IFIRST.NE.0) GO TO 10
C          IFIRST=1
C          PI2=ATAN2(0.,-1.)/2.
C          CON=90./PI2
C          SALF=SIN(11.7/CON)
C          CALF=COS(11.7/CON)
C          SGAM=SIN(23.5/CON)
C          CGAM=COS(23.5/CON)
C          SASG=SALF*SGAM
C          SACG=SALF*CGAM
C          CASG=CALF*SGAM
C          CACG=CALF*CGAM
C          W=PI2/6.*(1.+1./365.256)
C
C          MAIN ENTRY POINT. SET UP THE THE SINES AND COSINES REQUIRED
C          BY THE TRANSFORMATIONS.
10      WT=(UT-16.6+(DAYYR-172.)*24.)*W
C          CWT=-WT/365.256
C          SSMLT=SIN(WT)
C          CSMLT=COS(WT)
C          SBWT=SIN(CWT)
C          CBWT=COS(CWT)
C          SMLSWT=SSMLT*SBWT
C          SMLCWT=SSMLT*CBWT
C          CMLSWT=CSMLT*SBWT
C          CMLCWT=CSMLT*CBWT
C
C          DETERMINE THE COMPONENTS OF THE DIPOLE AXIS IN ECCLIPITIC
C          COORDINATES
C          ZX=CASG*CBWT+SACG*CMLCWT-SALF*SMLSWT
C          ZY=CASG*SBWT+SACG*CMLSWT+SALF*SMLCWT
C          ZZ=CACG-SASG*CSMLT
C
C          CALCULATE THE TILT ANGLE
C          PSI=ACOS(ZX)
C          OSP=1./(SIN(PSI))
C          TILT=CON*(PI2-PSI)
C
C          DETEMINE THE COMPONENTS OF THE GEOMAGNETIC X AXIS IN ECCLIPITIC
C          COORDINATES
C          XX=CACG*CMLCWT-SASG*CBWT-CALF*SMLSWT
C          XY=CACG*CMLSWT-SASG*SBWT+CALF*SMLCWT
C          XZ=-CASG*CSMLT-SACG
C
C          OBTAIN THE ROTATION SINES AND COSINES
C          SINPHE=(XY*ZZ-XZ*ZY)*OSP
C          COSPHE=(XX*(ZZ*ZZ+ZY*ZY)-ZX*(XY*ZY+XZ*ZZ))*OSP
C          RETURN
C          END

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SUBROUTINE BXYZMU(XX,BF,TILT)

VERSION 11/01/76

PURPOSE

TO CALCULATE THE CONTRIBUTION TO THE EARTHS MAGNETIC FIELD BY SOURCES EXTERNAL TO THE EARTH. NO INTERNAL FIELD IS INCLUDED IN THIS ROUTINE.

METHOD

THE ROUTINE INCLUDES THE FIELD CONTRIBUTIONS FROM THE MAGNETOPAUSE CURRENTS, AND CURRENTS DISTRIBUTED THROUGHOUT THE MAGNETOSPHERE (THE TAIL AND RING CURRENTS). IT IS VALID FOR ALL TILTS OF THE EARTHS DIPOLE AXIS AND IS VALID DURING QUIET MAGNETIC CONDITIONS.

A GENERALIZED ORTHONORMAL LEAST SQUARES PROGRAM WAS USED TO FIT THE COEFFICIENTS OF A POWER SERIES (INCLUDING EXPONENTIAL TERMS) THROUGH FOURTH ORDER IN SPACE AND THIRD ORDER IN TILT. THIS EXPANSION HAS BEEN OPTIMIZED FOR THE NEAR EARTH REGION AND IS VALID TO 15 EARTH RADII. OUTSIDE OF THIS REGION THE FIELD DIVERGES RAPIDLY AND A TEMPLATE SETS THE FIELD TO ZERO. IN ORDER TO IMPROVE COMPUTATIONAL SPEED THE FIELD IS SET TO ZERO BELOW 2 EARTH RADII. (IN THIS REGION THE EARTHS INTERNAL FIELD DOMINATES AND THE VARIATIONS EXCPRESSED BY THIS EXPANSION IS NOT SUFFICIENTLY ACCURATE THE PREDICT VARIATIONS ON THE EARTHS SURFACE)

THE POWER SERIES REPRESENTING THE MAGNETIC FIELD IS  
BX=SUM OVER I,J,K OF ( A(I,J,K)\*X\*\*(I-1)\*Y\*\*(2\*J-2)\*Z\*\*(K-1)  
+ B(I,J,K)\*X\*\*(I-1)\*Y\*\*(2\*J-2)\*Z\*\*(K-1)\*EXP(-.06\*R\*\*2))  
I GOES FROM 1 TO 5, J FROM 1 TO 3, K FROM 1 TO 5  
THE SUM OF I + 2\*J + K IS LESS THAN OR EQUAL TO 9  
BY=SUM OVER I,J,K OF ( C(I,J,K)\*X\*\*(I-1)\*Y\*\*(2\*J-1)\*Z\*\*(K-1)  
+ D(I,J,K)\*X\*\*(I-1)\*Y\*\*(2\*J-1)\*Z\*\*(K-1)\*EXP(-.06\*R\*\*2))  
I GOES FROM 1 TO 5, J FROM 1 TO 3, K FROM 1 TO 5  
THE SUM OF I + 2\*J+1 + K IS LESS THAN OR EQUAL TO 9  
BZ=SUM OVER I,J,K OF ( E(I,J,K)\*X\*\*(I-1)\*Y\*\*(2\*J-2)\*Z\*\*(K-1)  
+ F(I,J,K)\*X\*\*(I-1)\*Y\*\*(2\*J-2)\*Z\*\*(K-1)\*EXP(-.06\*R\*\*2))  
I GOES FROM 1 TO 5, J FROM 1 TO 3, K FROM 1 TO 5  
THE SUM OF I + 2\*J + K IS LESS THAN OR EQUAL TO 9  
THE COEFFICIENTS A-F ARE DEPENDENT ONLY ON POSITION AND  
ARE RECALCULATED EACH TIME THE TILT OF THE DIPOLE IS CHANGED.  
THE COEFFICIENTS A-F ARE DETERMINED FROM THE TILT DEPENDENT  
CONSTANTS AA-FF BY THE FOLLOWING EXPRESSIONS  
A(I,J,K)=AA(I,J,K,1)\*TILT\*\*(K-1-(K-1)/2\*2)  
+AA(I,J,K,2)\*TILT\*\*(K+1-(K-1)/2\*2)  
B(I,J,K)=BB.....  
C(I,J,K)=CC.....  
D(I,J,K)=DD.....  
E(I,J,K)=EE(I,J,K,1)\*TILT\*\*(K-(K)/2\*2)  
+EE(I,J,K,2)\*TILT\*\*(K+2-(K)/2\*2)  
F(I,J,K)=FF.....

INPUT -- CALLING SEQUENCE

XX A REAL ARRAY GIVING THE POSITION WHERE THE MAGNETIC FIELD IS TO BE EVALUATED. XX(1), XX(2), XX(3) ARE RESPECTIVELY THE X, Y, AND Z SOLAR MAGNETIC COORDINATES IN EARTH RADII. Z IS ALONG THE EARTHS NORTH DIPOLE AXIS, X IS PERPENDICULAR TO Z AND IN THE PLANE CONTAINING THE Z AXIS AND THE SUN-EARTH LINE, Y IS PERPENDICULAR TO X AND Z FORMING A RIGHT HANDED COORDINATE SYSTEM. X IS POSITIVE IN THE SOLAR DIRECTION.  
TILT IC THE TILT OF THE DIPOLE AXIS IN DEGREES. IT IS

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C          THE COMPLEMENT OF THE ANGLE BETWEEN THE NORTH DIPOLE
C          AXIS AND THE SOLAR DIRECTION (PSI). TILT=90-PSI.
C
C  OUTPUT -- CALLING SEQUENCE
C    BF      A REAL ARRAY CONTAINING THE X, Y, AND Z COMPONENTS OF
C            THE MAGNETOSPHERIC MAGNETIC FIELD IN GAMMA. BF(1),
C            BF(2) AND BF(3) ARE THE BX, BY, BZ COMPONENTS.
C
C  CONSTANTS
C    AA,BB,CC,DD,EE,FF ARE REAL ARRAYS CONTAINING THE TILT DEPENDENT
C            COEFFICIENTS.
C            AA(I,J,K,L) ARE STORED SUCH THAT L VARIES MOST RAPIDLY
C            FOLLOWED IN ORDER BY K, J AND I. I VARIES THE SLOWEST.
C            THE ARRAY IS CLOSE PACKED AND ALL COEFFICIENTS THAT
C            ARE ZERO BECAUSE OF SYMMETRY OR BECAUSE THE CROSS TERM
C            POWER IS TOO LARGE ARE DELETED.
C
C  VARIABLES
C    A,B,C,D,E,F THE TILT INDEPENDENT COEFFICIENTS. THEIR USE
C            IS DESCRIBED UNDER METHOD.
C    ITA      A REAL ARRAY WHICH CONTAINS THE SYMMETRY OF THE TILT
C            DEPENDENCE FOR EACH OF THE A AND B COEFFICIENTS
C            ITA(1) HAS THE SYMMETRY INFORMATION FOR A(1,1,1,1)
C                AND A(1,1,1,2)
C            ITA(2) HAS THE SYMMETRY INFORMATION FOR A(1,1,2,1)
C                AND A(1,1,2,2) ETC.
C            IF ITA = 1 TILT SYMMETRY IS EVEN WITH RESPECT TO Z SYM.
C            IF ITA = 2 TILT SYMMETRY IS ODD WITH RESPECT TO Z SYM.
C    ITB      SYMMETRY POINTER FOR C AND D ARRAYS
C    ITC      SYMMETRY POINTER FOR E AND F ARRAYS
C    X        X COMPONENT OF POSITION
C    Y        Y COMPONENT OF POSITION
C    Z        Z COMPONENT OF POSITION
C    Y2       Y**2
C    Z2       Z**2
C    R2       X**2 + Y**2 + Z**2
C    R        SQRT(R2)
C    I        DO LOOP VARIABLE. IN THE FIELD EXPANSION LOOP IT
C            REPRESENTS THE POWER TO WHICH X IS CURRENTLY RAISED
C            I.E. X**(I-1)
C    J        DO LOOP VARIABLE. ALSO Y**(2*J-2)
C    K        DO LOOP VARIABLE. ALSO Z**(K-1)
C    XB       X**(I-1)
C    YEXB     X**(I-1)*Y**(2*J-2)
C    ZEYEXB   X**(I-1)*Y**(2*J-2)*Z**(K-1)
C    IJK      I + 2*J + K
C    II       POINTS TO THE ARRAY LOCATION WHERE THE CURRENT POWER
C            SERIES COEFFICIENT FOR BX IS LOCATED
C    JJ       BY COEFFICIENT LOCATION POINTER
C    KK       BZ COEFFICIENT LOCATION POINTER
C    BX,BY,BZ ARE USED TO CONSTRUCT THE MAGNETIC FIELD WITHIN THE
C            POWER SERIES LOOP.
C    EXPR     EXP(-.06*R2)
C    TILTL    HOLDS THE LAST VALUE OF THE TILT FOR WHICH THE TILT
C            INDEPENDENT COEFFICIENTS A-F WERE CALCULATED
C    TT       A REAL ARRAY HOLDING THE POWERS OF THE TILT.
C            TT(1)=TILT**0, TT(2)=TILT**1, ETC.
C    CON      =0 FOR R LESS THAN 2
C            =1 FOR R GREATER THAN 2.5
C            GOES FROM 0 TO 1 IN THE REGION 2 TO 2.5
C
C  FOR MORE INFORMATION CALL OR WRITE K. A. PFITZER OR W. P. OLSON
C  AT MCDONNELL DOUGLAS ASTRONAUTICS CO. 5301 BOLSA AVE, HUNTINGTON
C  CALIF., PHONE (714) 896-3231.

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C

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DIMENSION BF(3),XX(3),AA(64),BB(64),CC(44),DD(44),EE(64),FF(64),
*A(32),B(32),C(22),D(22),E(32),F(32),TT(4),ITA(32),ITB(22),ITC(32)
DATA (ITA(I),I=1,32) /2,1,2,1,2,2,1,2,1,2,1,2,1,2,1,2,2,1,2,2,2,1,
*2,1,2,1,2,1,2,2,2,1/
DATA (ITB(I),I=1,22) /2,1,2,1,2,2,1,2,2,2,1,2,1,2,1,2,1,2,2,2,1,2/
DATA (ITC(I),I=1,32) /1,2,1,2,1,1,2,1,2,1,2,1,2,1,2,1,1,2,1,1,1,2,
*1,2,1,2,1,2,1,1,1,2/
DATA (AA(I),I=1,64)/-2.26836E-02,-1.01863E-04, 3.42986E+00, TOTAL
*-3.12195E-04, 9.50629E-03,-2.91512E-06,-1.57317E-03, 8.62856E-08, TOTAL
*-4.26478E-05, 1.62924E-08,-1.27549E-04, 1.90732E-06,-1.65983E-02, TOTAL
* 8.46680E-09,-5.55850E-05, 1.37404E-08, 9.91815E-05, 1.59296E-08, TOTAL
* 4.52864E-07,-7.17669E-09, 4.98627E-05, 3.33662E-10,-5.97620E-02, TOTAL
* 1.60669E-05,-2.29457E-01,-1.43777E-04, 1.09403E-03,-9.15606E-07, TOTAL
* 1.60658E-03,-4.01198E-07,-3.15064E-06, 2.03125E-09, 4.92887E-04, TOTAL
*-1.80676E-07,-1.12022E-03, 5.98568E-07,-5.90009E-06, 5.16504E-09, TOTAL
*-1.48737E-06, 4.83477E-10,-7.44379E-04, 3.82472E-06, 7.41737E-04, TOTAL
*-1.31468E-05,-1.24729E-04, 1.92930E-08,-1.91764E-04,-5.30371E-08, TOTAL
* 1.38186E-05,-2.81594E-08, 7.46386E-06, 2.64404E-08, 2.45049E-04, TOTAL
*-1.81802E-07,-1.00278E-03, 1.98742E-06,-1.16425E-05, 1.17556E-08, TOTAL
*-2.46079E-06,-3.45831E-10, 1.02440E-05,-1.90716E-08,-4.00855E-05, TOTAL
* 1.25818E-07/
DATA (BB(I),I=1,64)/ 9.47753E-02, 1.45981E-04,-1.82933E+00, TOTAL
* 5.54882E-04, 5.03665E-03,-2.07698E-06, 1.10959E-01,-3.45837E-05, TOTAL
*-4.40075E-05, 5.06464E-07,-1.20112E-03, 3.64911E-06, 1.49849E-01, TOTAL
*-7.44929E-05, 2.46382E-04, 9.65870E-07,-9.54881E-04, 2.43647E-07, TOTAL
* 3.06520E-04, 3.07836E-07, 6.48301E-03, 1.26251E-06,-7.09548E-03, TOTAL
*-1.55596E-05, 3.06465E+00,-7.84893E-05, 4.95145E-03, 3.71921E-06, TOTAL
*-1.52002E-01, 6.81988E-06,-8.55686E-05,-9.01230E-08,-3.71458E-04, TOTAL
* 1.30476E-07,-1.82971E-01, 1.51390E-05,-1.45912E-04,-2.22778E-07, TOTAL
* 6.49278E-05,-3.72758E-08,-1.59932E-03, 8.04921E-06, 5.38012E-01, TOTAL
*-1.43182E-04, 1.50000E-04, 5.88020E-07,-1.59000E-02, 1.60744E-06, TOTAL
* 3.17837E-04, 1.78959E-07,-8.93794E-03, 6.37549E-06, 1.27887E-03, TOTAL
*-2.45878E-07,-1.93210E-01, 6.91233E-06,-2.80637E-04,-2.57073E-07, TOTAL
* 5.78343E-05, 4.52128E-10, 1.89621E-04,-4.84911E-08,-1.50058E-02, TOTAL
* 6.21772E-06/
DATA (CC(I),I=1,44)/-1.88177E-02,-1.92493E-06,-2.89064E-01, TOTAL
*-8.49439E-05,-4.76380E-04,-4.52998E-08, 1.61086E-03, 3.18728E-07, TOTAL
* 1.29159E-06, 5.52259E-10, 3.95543E-05, 5.61209E-08, 1.38287E-03, TOTAL
* 5.74237E-07, 1.86489E-06, 7.10175E-10, 1.45243E-07,-2.97591E-10, TOTAL
*-2.43029E-03,-6.70000E-07,-2.30624E-02,-6.22193E-06,-2.40815E-05, TOTAL
* 2.01689E-08, 1.76721E-04, 3.78689E-08, 9.88496E-06, 7.33820E-09, TOTAL
* 7.32126E-05, 8.43986E-08, 8.82449E-06,-6.11708E-08, 1.78881E-04, TOTAL
* 8.62589E-07, 3.43724E-06, 2.53783E-09,-2.04239E-07, 8.16641E-10, TOTAL
* 1.68075E-05, 7.62815E-09, 2.26026E-04, 3.66341E-08, 3.44637E-07, TOTAL
* 2.25531E-10/
DATA (DD(I),I=1,44)/ 2.50143E-03, 1.01200E-06, 3.23821E+00, TOTAL
* 1.08589E-05,-3.39199E-05,-5.27052E-07,-9.46161E-02,-1.95413E-09, TOTAL
*-4.23614E-06, 1.43153E-08,-2.62948E-04, 1.05138E-07,-2.15784E-01, TOTAL
*-2.20717E-07,-2.65687E-05, 1.26370E-08, 5.88917E-07,-1.13658E-08, TOTAL
* 1.64385E-03, 1.44263E-06,-1.66045E-01,-1.46096E-05, 1.22811E-04, TOTAL
* 3.43922E-08, 9.66760E-05,-6.32150E-07,-4.97400E-05,-2.78578E-08, TOTAL
* 1.77366E-02, 2.05401E-07,-1.91756E-03,-9.49392E-07,-1.99488E-01, TOTAL
*-2.07170E-06,-5.40443E-05, 1.59289E-08, 7.30914E-05, 3.38786E-08, TOTAL
*-1.59537E-04,-1.65504E-07, 1.90940E-02, 2.03238E-06, 1.01148E-04, TOTAL
* 5.20815E-08/
DATA (EE(I),I=1,64)/-2.77924E+01,-1.01457E-03, 9.21436E-02, TOTAL
*-8.52177E-06, 5.19106E-01, 8.28881E-05,-5.59651E-04, 1.16736E-07, TOTAL
*-2.11206E-03,-5.35469E-07, 4.41990E-01,-1.33679E-05,-7.18642E-04, TOTAL
* 6.17358E-08,-3.51990E-03,-5.29070E-07, 1.88443E-06,-6.60696E-10, TOTAL
*-1.34708E-03, 1.02160E-07, 1.58219E-06, 2.05040E-10, 1.18039E+00, TOTAL
* 1.58903E-04, 1.86944E-02,-4.46477E-06, 5.49869E-02, 4.94690E-06, TOTAL
*-1.18335E-04, 6.95684E-09,-2.73839E-04,-9.17883E-08, 2.79126E-02, TOTAL
*-1.02567E-05, 1.25427E-04, 3.07143E-08,-5.31826E-04,-2.98476E-08, TOTAL

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*-4.89899E-05, 4.91480E-08, 3.85563E-01, 4.16966E-05, 6.74744E-04, TOTAL
*-2.08736E-07, -3.42654E-03, -3.13957E-06, -6.31361E-06, -2.92981E-09, TOTAL
*-2.63883E-03, -1.32235E-07, -6.19406E-06, 3.54334E-09, 6.65986E-03, TOTAL
*-5.81949E-06, -1.88809E-04, 3.62055E-08, -4.64380E-04, -2.21159E-07, TOTAL
*-1.77496E-04, 4.95560E-08, -3.18867E-04, -3.17697E-07, -1.05815E-05, TOTAL
* 2.22220E-09/
DATA (FF(I), I=1, 64) / -5.07092E+00, 4.71960E-03, -3.79851E-03, TOTAL
*-3.67309E-06, -6.02439E-01, 1.08490E-04, 5.09287E-04, 5.62210E-07, TOTAL
* 7.05718E-02, 5.13160E-06, -2.85571E+00, -4.31728E-05, 1.03185E-03, TOTAL
* 1.05332E-07, 1.04106E-02, 1.60749E-05, 4.18031E-05, 3.32759E-08, TOTAL
* 1.20113E-01, 1.40486E-05, -3.37993E-05, 5.48340E-09, 9.10815E-02, TOTAL
*-4.00608E-04, 3.75393E-03, -4.69939E-07, -2.48561E-02, 1.31836E-04, TOTAL
*-2.67755E-04, -7.60285E-08, 3.04443E-03, -3.28956E-06, 5.82367E-01, TOTAL
* 5.39496E-06, -6.15261E-04, 4.05316E-08, 1.13546E-02, -4.26493E-06, TOTAL
*-2.72007E-02, 5.72523E-08, -2.98576E+00, 3.07325E-05, 1.51645E-03, TOTAL
* 1.25098E-06, 4.07213E-02, 1.05964E-05, 1.04232E-04, 1.77381E-08, TOTAL
* 1.92781E-01, 2.15734E-05, -1.65741E-05, -1.88683E-09, 2.44803E-01, TOTAL
* 1.51316E-05, -3.01157E-04, 8.47006E-08, 1.86971E-02, -6.94074E-06, TOTAL
* 9.13198E-03, -2.38052E-07, 1.28552E-01, 6.92595E-06, -8.36792E-05, TOTAL
*-6.10021E-08/
DATA TILT/99./
C
C SET UP SOME OF THE INITIAL POSITION VARIABLES
X=XX(1)
Y=XX(2)
Z=XX(3)
Y2=Y**2
Z2=Z**2
R2=X**2+Y2+Z2
C
C SET MAGNETIC FIELD VARIABLES TO ZERO
BX=0.
BY=0.
BZ=0.
C
C CHECK TO SEE IF POSITION IS WITHIN REGION OF VALIDITY
CON=1.
C IF DISTANCE TOO LARGE TAKE ERROR EXIT
IF(R2.GT.225.) GO TO 50
C IF DISTANCE TOO SMALL SET FIELD TO ZERO AND EXIT
IF(R2.LT.4.) GO TO 40
IF(R2.LT.6.25) CON=CON*(R2-4.0)/2.25
C
C IF TILT HAS NOT CHANGED, GO DIRECTLY TO FIELD CALCULATION
IF(TILT.EQ.TILT) GO TO 6
C SET UP POWERS OF TILT
TILT=TILT
TT(1)=1
TT(2)=TILT
TT(3)=TILT**2
TT(4)=TILT*TT(3)
C
C SET UP THE X AND Z COMPONENT TILT INDEPENDENT COEFFICIENTS
DO 1 I=1, 32
J=(I-1)*2+1
K=ITA(I)
A(I)=AA(J)*TT(K)+AA(J+1)*TT(K+2)
B(I)=BB(J)*TT(K)+BB(J+1)*TT(K+2)
K=ITC(I)
E(I)=EE(J)*TT(K)+EE(J+1)*TT(K+2)
F(I)=FF(J)*TT(K)+FF(J+1)*TT(K+2)
1 CONTINUE
C
C SET UP THE Y COMPONENT TILT INDEPENDENT COEFFICIENTS

```

```

DO 2 I=1,22
J=(I-1)*2+1
K=ITB(I)
C(I)=CC(J)*TT(K)+CC(J+1)*TT(K+2)
D(I)=DD(J)*TT(K)+DD(J+1)*TT(K+2)
2 CONTINUE
6 EXPR=EXP(-0.06*R2)
C
C INITIALIZE THE POINTERS
II=1
JJ=1
KK=1
XB=1.
C
C BEGIN SUM OVER X
DO 30 I=1,5
YEXB=XB
C
C BEGIN SUM OVER Y
DO 20 J=1,3
IF(I+2*J.GT. 8) GO TO 25
ZEYEXB=YEXB
IJK=I+2*J+1
K=1
C
C Z LOOP STARTS HERE
10 BZ=BZ+(E(KK)+F(KK)*EXPR)*ZEYEXB
KK=KK+1
BX=BX+(A(II)+B(II)*EXPR)*ZEYEXB
II=II+1
IF(IJK.GT. 8) GO TO 15
BY=BY+(C(JJ)+D(JJ)*EXPR)*ZEYEXB*Y
JJ=JJ+1
ZEYEXB=ZEYEXB*Z
IJK=IJK+1
K=K+1
IF(IJK.LE.9.AND.K.LE.5) GO TO 10
15 YEXB=YEXB*Y2
20 CONTINUE
25 XB=XB*X
30 CONTINUE
C
C SET UP THE OUTPUT ARRAY, MULTIPLY BY CON. CON IS NORMALY ONE
C BUT INSIDE OF R=2.5 IT GOES TO ZERO. INSIDE R=2 IT IS ZERO.
40 BF(1)=BX*CON
BF(2)=BY*CON
BF(3)=BZ*CON
RETURN
C
C ERROR EXIT IF OUTSIDE OF R = 15.
50 WRITE(6,60) XX
60 FORMAT(4H X= ,E10.3,4H Y= ,E10.3,4H Z= ,E10.3,76H IS OUTSIDE THE
*VALID REGION--POWER SERIES DIVERGES BFIELD IS SET TO ZERO )
GO TO 40
END

```

## Appendix C

### Subroutine INVARM

This appendix presents a listing of subroutine INVARM, the central routine for developing the new radiation belt models. The operation and functions performed by this routine are spelled out in section 2.3. The routine is preceded by a test routine that presents a sample of its capabilities and also provides a means for assessing its operation.

The test routine varies the distance, latitude, longitude, and universal time and asks the INVARM program to calculate the invariant for 18 different pitch angles at each location.

All input and out variables are passed via the arguments of the subroutine call. It is possible to limit the number of terms used by the internal field routine by setting NMAX to a value between 2 and 10. This must be done via labeled COMMON /GCOM/. The internal field routine checks the value of this variable. If it is set to zero as it normally is when labeled COMMON is preset by the loader or set to any value other than 2 through 10, then the internal field routine uses the maximum coefficients defined for the IGRF field. For the coefficients supplied with this program an NMAX of 11 is used. Labeled COMMON /MOMENT/ contains the dipole moment of the main field as calculated from the coefficient set that is in use. This may be used by any routine that requires it.

The calling argument for the routine are

#### Input variables

XLAT	The geographic latitude measured in degrees from the geographic equator, plus is north and minus is south.
XLONG	The geographic east longitude measured from Greenwich England (0-360)
R	The radial distance from the center of the earth in unit of earth radii. One radius is 6371.2 km.
YR	The year of the calculation. This variable is used by the internal magnetic field routine to calculate the epoch of the magnetic field. Whenever this value changes by 0.1 years the coefficient set for the internal field is updated. It is suggested that this value not be changed unless the drift of the internal field during the calculations is important to the analysis. The coefficients are valid from 1945 to the present. Dates earlier than 1945, will cause the routine to use the 1945 coefficient set. Use caution in predicting the field far into the future. Historically, predicting the field into the future has not been very successful.
DAY	The day of the year. January 1 is DAY = 1. This is a floating point variable but it should be limited to whole numbers.

TIME	The universal time in hours. This is a floating point number should represent the correct universal time to the required precision.
JSWITCH	An integer variable that controls whether the external field is included in the calculation. JSWITCH negative uses the internal field only, JSWITCH = 0 or positive uses the internal plus external magnetic field.
NUMANG	An integer variable that specifies the number of pitch angles for which the invariant must be calculated.
PANGLE	A single variable or an array that contains the pitch angles for which the routine is to calculate the invariant. The dimension of PANGLE must be equal to or greater than NUMANG. If NUMANG is 1, then PANGLE may be a simple undimensioned variable.

#### Output parameters

EL	A simple variable or an array dimensioned to at least NUMANG that will contain the L value for the specified location and pitch angle. If no L could be calculated EL is set to -1.0, if the mirror point is below $1.03 R_E$ or EL is set to 100 if the field line is open or the maximum number of steps is reached by the routine.
BLOCAL	The value of the magnetic field at the observation point.
BMIN	The minimum value of the magnetic field along the particle line of force.
XMLONG	The magnetic longitude of the minimum B point on the magnetic line of force. 0 degrees is local midnight.
XMLAT	The magnetic latitude of the observation point.
BMAXAN	The Mirror point magnetic field for each of the pitch angles. BMAXAN can either be a simple variable or and array dimensioned at least to order NUMANG.
XJ	The value of the second invariant for each pitch angle. XJ can either be a simple variable or and array dimensioned at least to order NUMANG.
DENSTY	The column density of the atmosphere along the particle's bounce path in $\text{gm/cm}^2$ . DENSTY can either be a simple variable or and array dimensioned at least to order NUMANG.

```

COMMON/GCOM/ ST,CT,SP,CP,AOR,BT,BP,BR,NMAX,YEARI
DIMENSION BMAXAN(20),XJ(20),ANGLE(20),EL(20),DENSTY(20),ALPHEQ(20)
common/temp/nlast,n2last

C
C   THIS PROGRAM PROVIDES A TEST RUN OF THE L VALUE SUBROUTINES
C

CHARACTER*6 IAR(3)
DATA IAR/6H INT ,6H IN+EX,6H L AVE/
DO 500 I=1,18
  ANGLE(I)=90-(I-1)*5

500  CONTINUE
    NUMANG=18
    IDSWIT=1
    LN=100
    YEAR=1990
    DA=1
    DO 5 IU=1,1,12
      UT=IU-1
      LN=100
      DO 4 IL=1,31,30
        FLAT=IL-1
        DO 3 ILG=1,181,180
          XLONG=ILG
          DO 2 IR=2,8,2
            R=IR-.5
            DO 1 IC=1,2
              call gettim(ihr,imin,isech,i100)
              btime=float(imin*60+isech)+float(i100)/100.
              CALL INVARM(FLAT,XLONG,R,YEAR,DA,UT,IC-2,ANGLE,NUMANG,
*EL,BLOC,BM,XMLONG,XMLAT,BMAXAN,XJ,DENSTY)
              call gettim(jhr,jmin,jsec,j100)
              time=float(jmin*60+jsec)+float(j100)/100.-btime
              IF(IC.EQ.1)WRITE(*,103)
103  FORMAT(1H1)
              WRITE(*,101)FLAT,XLONG,R,YEAR,DA,UT,IAR(IC),BLOC,BM,XMLAT,XMLONG
101  FORMAT(//,' Lat = ',f6.1,' Long = ',f7.1,' R = ',f4.1,
*//,' Year = ',f7.1,' Day = ',f5.0,' UT = ',f6.2,' Field = ',A6,
*//,' Blocal = ',F8.5,' Bmin = ',F8.5,' Mlat = ',f8.3,
*' Mlong = ',f9.3)
              WRITE(*,102)
102  FORMAT(//,' P. Angle   B mir      2nd Inv.   L           Density',
*'      Eq. Pitch Angle',/)
              LN=0
              DO 50 I=1,NUMANG
50    ALPHEQ(I)=ASIN(SQRT(BM/BLOC)*SIN(ANGLE(I)*.01745329))/.01745329
              write(*,100)(angle(i),bmaxan(i),xj(i),el(i),densty(i),
*alpheq(i),i=1,numang)
10    write(*,*)nlast,n2last,time
100  format(0Pf6.1,2f11.5,f8.3,1PE15.5,0PF13.2)
1    CONTINUE
2    CONTINUE
3    CONTINUE
4    CONTINUE
5    CONTINUE
      END

```

SUBROUTINE INVARM(XLAT,XLONG,R,YR,DAY,TIME,JSWTC,PANGLE,  
 \*NUMANG,EL,BLOCAL,BMIN,XMLONG,XMLAT,BMAXAN,XJ,DENSTY)

# PURPOSE

CALCULATE THE VARIOUS MAGNETIC COORDINATES OF THE PARTICLES' DRIFT SHELL. CALCULATE THE 1ST AND 2ND ADIABATIC INVARIANTS AND THE L PARAMETER FOR A NUMBER OF PITCH ANGLES AT THE SPECIFIED LOCATION. ALSO DETERMINE THE LOCAL MAGNETIC FIELD, THE MAGNETIC LATITUDE, THE MINIMUM MAGNETIC FIELD ON THE FIELD LINE AND THE MAGNETIC LONGITUDE AT THE FIELD MINIMUM.

## INPUT -- ARGUMENT LIST

XLAT GEOCENTRIC GEOGRAPHIC LATITUDE IN DEGREES (+ IS NORTH)  
 XLONG GEOCENTRIC GEOGRAPHIC LONGITUDE EAST OF GREENWHICH IN DEGREES  
 R GEOCENTRIC DISTANCE FROM THE EARTHS CENTER IN UNITS EARTH RADII, RE. RE=6371.2 KM  
 YR THE YEAR - USED BY THE INTERNAL MAGNETIC FIELD ROUTINE TO TAKE INTO ACCOUNT THE SECULAR VARIATIONS (E.G. JULY 15,1964 = 1964.54)  
 NOTE\*\*\* YR SHOULD BE CHANGED ONLY EVERY FEW DAYS OR MONTHS. NEW FIELD COEFFICIENTS MUST BE COMPUTED FOR EVERY CHANGE IN YR, THIS COULD CAUSE A LARGE INCREASE IN COMPUTER TIME. THE EARTHS FIELD CHANGES ONLY ABOUT .001 GAUSS/YEAR AT THE EARTHS SURFACE.  
 IF YR IS CHANGED BY MORE THAN .1 YEAR NEW FIELD COEFFS. ARE COMPUTED  
 DAY THE DAY OF YEAR (1.-366.). THE DAY IS USED BY THE MAGNETIC FIELD ROUTINE TO CALCULATE THE TILT OF THE DIPOLE AXIS FOR THE EXTERNAL FIELD ROUTINE  
 DAY MUST BE A WHOLE NUMBER AND DAY 1 IS JANUARY 1  
 TIME UNIVERSAL TIME IN HOURS (0.000-24.0000)  
 JSWTC A FLOW CONTROL VARIABLE  
 JSWTC = -1 OR NAEGATIVE, COMPUTE L USING INTERNAL FIELD ONLY  
 = 0 OR POSITIVE, COMPUTE L USING INTERNAL PLUS EXTERNAL FIELD  
 PANGLE A SINGLE PITCH ANGLE OR AN ARRAY OF PITCH ANGLES FOR THE INVARIANTS WILL BE CALCULATED. THE PITCH ANGLE MUST BE .LE. 90 AND GT.0 AND THE ARRAY MUST BE ORDERED IN DESCENDING ORDER (90, 80, 70,...)  
 NUMANG THE NUMBER OF ELEMENT IN THE PANGLE ARRAY

## OUTPUT PARAMETERS

EL A SINGLE VARIABLE OR AN ARRAY OF DIMENSION NUMANG. THIS RETURNS THE L VALUE CALCUATED FROM THE INVARIANT.  
 VARIABLE JSWTC  
 \*\*\*\*\*NOTE\*\*\*\*\*  
 SINCE THIS ROUTINE USES AN ACTUAL MAGNETOSPHERIC MAGNETIC FIELD, THE FIELD LINES ARE NOT ALL CLOSED. THUS L IS DEFINED ONLY IN THE INNER MAGNETOSPHERE (IN THE REGION OF CLOSED DRIFT SHELLS). AN ATTEMPT TO CALCULATE L OUTSIDE OF THIS REGION WILL SET EL TO 100 (EL=100), SET BMIN TO THE LOCAL FIELD VALUE AND SET XMLONG TO ZERO UNLESS MINIMUM B WAS PASSED PRIOR TO THE DETECTION OF THE ERROR  
 IF THE MIRROR POINT FOR A GIVEN PITCH ANGLE IS BELOW 200KM THEN EL IS SET TO -1  
 BLOCAL THE VALUE OF THE MAGNETIC FIELD AT THE INPUT POSITION (IN GAUSS)  
 BMIN THE MINIMUM VALUE OF B ALONG THE FIELD LINE IN GAUSS  
 XMLONG THE MAGNETIC LONGITUDE OF THE MAGNETIC FIELD MINIMUM MEASURED EAST OF THE PRIME MAGNETIC MERIDIAN (IN DEGREES).  
 A USER CONSTANT IN SUBROUTINE MGLONG ALLOWS THE USER



```

C      RMIN  THE VECTOR POSITION TO THE MAGNETIC MINIMUM
C      RMAG  THE MAGNITUDE OF THE DISTANCE TO BMIN
C      SER   ERROR CONTROL VARIABLE. THE INTEGRATION STOPS IF
C            THE CURRENT POSITION POINT IS WITHIN DISTANCE SER OF
C            BMAX
C      SF    OUTPUT OF THE INTERPOLATION SUBROUTINE INTERP. IT
C            INDICATES THE SCALAR DISTANCE ALONG THE FIELD WHERE
C            B IS EQUAL TO BMAX
C      SXJ   A REAL ARRAY WHICH SAVES THE INTEGRATION STEP VALUES
C            OF THE SECOND ADIABATIC INVARIANT
C      UT    UNIVERSAL TIME
C      XDS   TEMPORARY VALUE USED FOR OBTAINING DISTANCE TO COMPLETION
C            OF INTEGRATION
C      XJ    FINAL VALUE OF THE SECOND ADIABATIC INVARIANT
C      XL    A REAL ARRAY HOLDING THE PREVIOUS VALUE OF THE POSITION
C            VECTOR
C      XSV   A 3 DIMENSIONED REAL ARRAY HOLDING ALL OF THE POSITION
C            VECTORS ALONG THE INTEGRATION PATH
C      XXJ   INTERPOLATED VALUE OF THE SECOND ADIABATIC INVARIANT
C      YEAR  THE YEAR
C      ZP    THE Z COMPONENT OF THE POSITION VECTOR IN CENTERED
C            DIPOLE COORDINATES

```

VERSION 6/91

FOR MORE INFORMATION CALL OR WRITE K. A. PFITZER AT MCDONNELL  
DOUGLAS ASTRONAUTICS CO. 5301 BOLSA AVE, HUNTINGTON BEACH CALIF.  
PHONE (714) 896-3231.

```

COMMON/BXYZCM/YEAR, DAYYR, UT, KODE, JSW
COMMON /INTPAR/DS, DEL, N, IERFLG, XL(3), XSV(100, 3, 4),
*RSV(100), RMIN(3), RMAG, IDSW,
*QL(3), Q(3), BL(3), SXJ(100), DDS
common/temp/nlast, n2last
DIMENSION BB(100, 4), BB2(100, 4), B(3), B2(3), X(3), X2(3), S(100),
*S2(100), DEN(100), DEN2(100)
DIMENSION EL(*), PANGLE(*), BMAXAN(*), XJ(*), BLL(3), BLL2(3)
DIMENSION XX(3), BINTL(3), DENSTY(*)
DATA PICON/.01745329252/
DATA ERR/.0005/
DATA CONI/.95/

```

OBTAIN THE CARTESIAN COMPONENTS OF THE POSITION VECTOR

CHECK THE PITCH ANGLES, THEY MUST BE BETWEEN 90 AND 0 AND THEY MUST  
BE IN DESCENDING ORDER (IE. 90, 85, 80, ....

```

NMANG=NUMANG
CALL CHECK(PANGLE, NMANG, IER)
IF (IER.GT.0) THEN
WRITE(*,*) 'Pitch angle error, must be monotonic and >0 & <=90'
DO 5 I=1, NMANG
XJ(I)=-1
BMAXAN(I)=-1
EL(I)=-1
DENSTY(I)=-1
5 CONTINUE
RETURN
ENDIF

```

```

COSINE=COS(XLAT*PICON)
XX(1)=R*COSINE*COS(XLONG*PICON)
XX(2)=R*COSINE*SIN(XLONG*PICON)
XX(3)=R*SIN(XLAT*PICON)

```

```

C      ROTATE TO DIPOLE COORDINATES (FIRST ROTATE ABOUT Z 291 DEGREES
C      THEN ABOUT THE NEW Y 11.7 DEGREES TO THE DIPOLE AXIS)
C
C      ZP=(XX(1)*.3583679495-XX(2)*.9335804265)*.2027872954
C      *+XX(3)*.9792228106
C
C      EVALUATE THE MAGNETIC LATITUDE
C      XMLAT=90.-ACOS(ZP/R)/PICON
C
C      SET THE MAGNETIC LONGITUDE TO ZERO. IF MINIMUM B IS REACHED
C      PRIOR TO AN ERROR BEING DETECTED XMLONG IS UPDATED TO REFLECT
C      MAGNETIC LONGITUDE AT MINIMUM B
C      XMLONG=0.
C
C      SET UP THE COMMON BLOCK INPUT VARIABLES FOR THE MAGNETIC FIELD
C      SUBROUTINE
C      YEAR=YR
C      UT=TIME
C      DAYYR=DAY
C      JSW=JSWTC
C      KODE=1
C      IBEFLG=0
C
C      EVALUATE THE MAGNETIC FIELD AT THE STARTING POINT
C      CALL BMNEXT(XX,B,BB(2,1))
C      BLOCAL = BB(2,1)
C      BB2(2,1)=BB(2,1)
C
C      SAVE THE INITIAL POSITION AND MAGNETIC FIELD VECTORS
C      DO 10 I=1,3
C          BINTL(I)=B(I)
C          B2(I)=B(I)
C          XL(I)=XX(I)
C          X2(I)=XX(I)
C          XSV(2,I,1)=XX(I)
10  CONTINUE
C      RSV(2)=R
C
C      EXIT THE ROUTINE IF POSITION IS OVER THE POLAR CAP OR DISTANCE
C      IS TOO LARGE OR MAGNETIC FIELD IS TOO WEAK
C      IF(ABS(XMLAT).GT.75..OR.R.GT.12..OR.BB(2,1).LT..00025) THEN
C          NMANG=0
C          BMAXAN(1)=100.
C          GOTO 218
C      ENDIF
C
C      SET UP THE INITIAL VALUES FOR THE VARIABLES
C      NLAST=2
C      N2LAST=2
C      S(2)=0.
C      S2(2)=0.
C      DEN(2)=0
C      DEN2(2)=0
C      DDS=100.
C      MINFLG=0
C
C      SET BMIN TO LOCAL FIELD VALUE. IF MINIMUM B IS REACHED PRIOR
C      TO ERROR DETECTION BMIN IS UPDATED TO MINIMUM B.
C      BMIN=BB(2,1)
C
C      SET UP THE ERROR LIMITS FOR THE INTEGRATION
C      SER=SQRT(ERR)
C      STEP SIZE GOES AS ERROR TO THE .25 POWER
C      DEL=-2.5*ERR** .25

```

```

      DS=SER
C
C      STEP ONCE IN THE INCREASING FIELD DIRECTION AND SET STEP
C      PARAMETERS TO INTEGRATE IN THE DECREASING FIELD DIRECTION
      IFLAG=0
      IF(XMLAT.GT.0.)GO TO 30
20    DEL=-DEL
      DS=-DS
30    N=2
      DO 31 I=1,3
        Q(I)=0
        X(I)=XL(I)
31    CONTINUE
      CALL INTGRT(X,B,BB,S,DEN)
      IFLAG=IFLAG+1
      IF((BB(3,1).LT.BB(2,1)).AND.(IFLAG.LE.1)) GOTO 20
      S(1)=S(3)
      DEN(1)=DEN(3)
      BB(1,1)=BB(3,1)
      DO 34 I=1,3
        XL(I)=X(I)
        BL(I)=B(I)
        Q(I)=0
        X(I)=XX(I)
        B(I)=BINTL(I)
34    CONTINUE
      RSV(1)=SQRT(XL(1)**2+XL(2)**2+XL(3)**3)
      DELSV=DEL
C
C      BEGIN THE FIELD LINE INTEGRATION.  THE INTEGRATION USES A VARIABLE
C      STEPSIZE WHICH IS DEPENDENT ON THE CURVATURE OF THE FIELD LINE
C      AND ON THE DISTANCE EACH POINT IS FROM EARTH CENTER (A MEASURE
C      OF THE MAGNETIC FIELD STRENGTH).  THE INITIAL INTEGRATION IS A
C      LINE INTEGRAL OF THE MAGNETIC FIELD UNIT VECTOR.  THIS INTEGRATION
C      LOOP ALSO SAVES ALL OF THE VARIABLES WHICH ARE LATER NEEDED TO
C      EVALUATE THE SECOND INTEGRAL INVARIANT.
C
      DO 216 IA=1,NMANG
      DEL=DELSV
      DDS=100
      BMAX=BB(2,1)/SIN(PANGLE(IA)*PICON)**2
      N=NLAST
      IF (IA.NE.1)THEN
        DO 41 I=1,3
          BL(I)=BLL(I)
41      CONTINUE
      DS=S(N)-S(N-1)
      CALL INTERP(BB(N-2,1),S(N-2),BMAX,SF,3)
      IF (ABS(SF).GT.ABS(S(N))) THEN
        XDS=SF-S(N)
        IF (ABS(XDS).LE.SER)GOTO 100
        DDS=CON1*XDS
      ENDIF
      ENDIF
C
40    CALL STEPSZ(X,B,BB)
45    CALL INTGRT(X,B,BB,S,DEN)
C
C      IF FIELD IS STILL DECREASING RELOOP
      IF(BB(N,1).LT.BB(N-1,1)) GO TO 40
C
C      IF MINIMUM VALUES HAVE BEEN CALCULATED, JUMP OVER MINIMUM ROUTINES
C      WHEN THE CURRENT VALUE OF B EXCEEDS THE LAST, FIND THE
C      INTERPOLATED MINIMUM MAGNETIC FIELD VALUE AND USE THIS VALUE TO

```

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C      UPDATE THE VALUE OF BMAX TO REFLECT THE AVERAGE DRIFT SHELL (IF
C      AVERAGE SHELLS ARE REQUIRED)
C      USE THE DISTANCE, SF, TO THE FIELD MINIMUM TO DETERMINE THE
C      MAGNETIC LONGITUDE OF THE FIELD MINIMUM
C
      IF(MINFLG.NE.0) GO TO 50
      CALL INTERP(BB(N-2,1),S(N-2),BMIN,SF,-1)
      CALL MGLONG(XSV(N-2,1,1),S(N-2),SF,XMLONG,RMIN(1),RMAG)
      MINFLG=1
C
C      CONTINUE STEPPING ALONG THE FIELD LINE AS LONG AS B IS LESS THAN
C      BMAX AND THE INTEGRATION IS MORE THAN A DISTANCE SER FROM BMAX
C      IF BMAX HAS BEEN EXCEEDED, EXIT TO INTERPOLATION SCHEME
C
50    IF(BB(N,1).GE.BMAX) GO TO 70
C      IF WE ARE OUTSIDE OF VALID REGION EXIT
      IF(IERFLG.NE.0) THEN
        NMANG=IA-1
        IF(IERFLG.GT.0) THEN
          BMAXAN(IA)=100
        ELSE
          BMAXAN(IA)=-1
        ENDIF
        GOTO 218
      ENDIF

      CALL INTERP (BB(N-2,1),S(N-2),BMAX,SF,3)
      DDS=100.
C
C      IF S DOES NOT INCREASE MONOTONICALLY, IGNORE INTERPOLATION
C      AND RELOOP
      IF(ABS(SF).LE.ABS(S(N))) GO TO 40
      XDS=SF-S(N)
C
C      IF WITHIN SER OF BMAX STOP INTEGRATION GO GET VALUE OF INVARIANT
      IF(ABS(XDS).LT.SER) GO TO 100
      DDS=CONI*XDS
C      RELOOP
      GO TO 40
C
C      THE FUNCTION SQRT(1-B/BMAX) DOES NOT EXIST FOR B GREATER THAN BMAX
C      IF PREVIOUS STEP IS NOT WITHIN SER OF BMAX INTERPOLATE TO FIND
C      A STEP SIZE THAT WILL GET CLOSE TO BUT NOT EXCEED BMAX
C
70    CALL INTERP(BB(N-2,1),S(N-2),BMAX,SF,3)
C
      IF(ABS(SF-S(N)).LT.SER) THEN
        CALL INTERP(BB(N-2,1),RSV(N-2),BMAX,RS,3)
        IF (RS.LT.1.03) THEN
          NMANG=IA-1
          BMAXAN(IA)=-1
          GOTO 218
        ENDIF
      ENDIF
C
C      SET UP THE STEP SIZE AND RESET INTEGRATION VALUES TO THE PREVIOUS
C      STEP
C
      N=N-1
      XDS=DS
      IF(ABS(SF).GT.ABS(S(N))) XDS=0.9*(SF-S(N))
C      IF THE STEP SIZE IS LESS THAN SER, THE PREVIOUS STEP IS CLOSE
C      ENOUGH EXIT TO INVARIANT CALCULATION

```

```

      IF (ABS(XDS) .LT. SER) GOTO 100
      IF (ABS(XDS) .GE. ABS(DS)) THEN
        DS=DS/2
      ELSE
        DS=XDS
      ENDIF
      DO 80 I=1,3
        X(I)=XL(I)
        Q(I)=QL(I)
        B(I)=BL(I)
80    CONTINUE
85    CALL INTGRT(X,B,BB,S,DEN)
C
C    IF LAST STEP IS STILL PAST BMAX TRY THE INTERPOLATION SCHEME AGAIN
90    IF (BB(N,1) .GT. BMAX) GO TO 70
C
C    INTERPOLATE TO SEE IF THE INTERPOLATION STEP IS CLOSE ENOUGH
C    TO BMAX. IF IT IS NOT, INTERPOLATE AGAIN AND TRY TO COME CLOSER
C
      CALL INTERP(BB(N-2,1),S(N-2),BMAX,SF,3)
C
C    IF WE ARE CLOSE ENOUGH EXIT THE INTEGRATION LOOP
      IF (ABS(SF-S(N)) .LT. SER) THEN
        CALL INTERP(BB(N-2,1),RSV(N-2),BMAX,RS,3)
        IF (RS .LT. 1.03) THEN
          NMANG=IA-1
          BMAXAN(IA)=-1
          GOTO 218
        ELSE
          GOTO 100
        ENDIF
      ENDIF
      DS=DS/2
      IF (ABS(SF) .GT. ABS(S(N))) DS=CONI*(SF-S(N))
      CALL INTGRT(X,B,BB,S,DEN)
      GO TO 90
C
C    THE FIELD MAXIMUM HAS NOW BEEN REACHED. THE STORED VALUES
C    OF THE MAGNETIC FIELD AND THE PATH LENGTH VALUES CAN NOW BE
C    USED TO EVALUATE THE SECOND INVARIANT.
C
100   IF (N .LT. 3) THEN
        XJ(IA)=0
        BMAXAN(IA)=BMAX
        GOTO 216
      ELSEIF (N .EQ. 3) THEN
        DS=.5*(S(N-1)-S(N))
        CALL INTGRT(X,B,BB,S,DEN)
        KS=2
      ELSE
        KS=3
      ENDIF
      NLAST=N
      DO 109 I=1,3
        BLL(I)=BL(I)
109   CONTINUE
C
C    CALL THE ROUTINE WHICH DETERMINES THE SECOND INVARIANT FROM
C    FROM THE STORED VALUES
C
110   CALL INVR(BMAX,BB,S)
C
C    INTERPOLATE TO GET THE BEST FIT

```

```

C      CALL INTERP (BB (N-2, 1), SXJ (N-2), BMAX, XXJ, KS)
C      CALL INTERP (BB (N-2, 1), DEN (N-2), BMAX, XDN, KS)
C
C      SAVE THE VALUES OF THE FIRST AND SECOND INVARIANT
C      XJ (IA) = ABS (XXJ)
C      DENSTY (IA) = ABS (XDN)
C      BMAXAN (IA) = BMAX
C
C      THE INTEGRAL HAS NOW BEEN EVALUATED FROM THE STARTING POINT
C      THROUGH THE MINIMUM VALUE OF B TO BMAX.
C
C      WE MUST INTEGRATE THE REST OF THE LINE --- TURN THE STARTING
C      POINTS AROUND AND RESET THE INITIAL VALUES AND INTEGRATE TO THE
C      OTHER BMAX
C
C      DEL = -DELSV
C      IF (IA.EQ.1) THEN
C          N=2
C          BB2 (1, 1) = BB (3, 1)
C          SXJ (1) = SXJ (3)
C          S2 (1) = S (3)
C          DEN2 (1) = DEN (3)
C          DS = S (2) - S (3)
C      ELSE
C          N = N2LAST
C          DO 117 I = 1, 3
C              BL (I) = BLL2 (I)
117      CONTINUE
C          DS = S2 (N) - S2 (N-1)
C          CALL INTERP (BB2 (N-2, 1), S2 (N-2), BMAX, SF, 3)
C          IF (ABS (SF) .GT. ABS (S2 (N))) THEN
C              XDS = SF - S2 (N)
C              IF (ABS (XDS) .LE. SER) GOTO 200
C              DDS = CONI * XDS
C          ENDIF
C      ENDIF
C      CALL STEPSZ (X2, B2, BB2)
C
C      IF (ABS (BB (2, 1) - BMAX) / BMAX .LT. ERR. OR. IBEFLG .NE. 0) GO TO 216
C      CALL INTERP (BB (2, 1), S (2), BMAX, SF, 1)
C      IF (ABS (SF) .LT. SER) THEN
C          CALL INTERP (BB (2, 1), SXJ (2), BMAX, XXJ, 1)
C          GOTO 215
C      ENDIF
C
C      IF (ABS (SF) .LT. ABS (DS)) DS = .7 * SF
C      DO 120 I = 1, 3
C          Q (I) = 0.
120      CONTINUE
C      N = N2LAST
C
C      GO TO 140
C
C      BEGIN INTEGRATING THE SECOND PART
130      CALL STEPSZ (X2, B2, BB2)
140      CONTINUE
C      CALL INTGRT (X2, B2, BB2, S2, DEN2)
C      DDS = 100.
C
C      STOP INTEGRATION IF BMAX HAS BEEN PASSED
C      IF (BB2 (N, 1) .GE. BMAX) GO TO 150
C      IF (IERFLG .NE. 0) THEN

```

```

        IF (IERFLG.GT.0) THEN
            BMAXAN(IA)=100
        ELSE
            BMAXAN(IA)=-1
        ENDIF
        NMANG=IA-1
        GOTO 218
    ENDIF

    CALL INTERP (BB2(N-2,1),S2(N-2),BMAX,SF,3)
C
C    IGNORE INTERPOLATION IF RESULT IS NOT MONOTONIC
    DDS=100
    IF (ABS(SF).LE.ABS(S2(N))) GOTO 130

    XDS=SF-S2(N)
C
C    STOP INTEGRATION IF WITHIN SER OF BMAX
    IF (ABS(XDS).LT.SER) GO TO 200
    DDS=CONI*XDS
    GO TO 130
C
C    BMAX HAS BEEN PASSED, BEGIN INTERPOLATION SCHEME TO FIND A POINT
C    CLOSE TO BMAX BUT LESS THAN IT.
C
150 CALL INTERP (BB2(N-2,1),S2(N-2),BMAX,SF,3)
    IF (ABS(SF-S2(N)).LE.SER) THEN
        CALL INTERP (BB2(N-2,1),RSV(N-2),BMAX,RS,3)
        IF (RS.LT.1.03) THEN
            NMANG=IA-1
            BMAXAN(IA)=-1
            GOTO 218
        ENDIF
    ENDIF

    N=N-1
    XDS=DS
    IF (ABS(SF).GT.ABS(S2(N))) XDS=0.9*(SF-S2(N))
    IF (ABS(XDS).LT.SER) GOTO 200
    IF (ABS(XDS).GE.ABS(DS)) THEN
        DS=DS/2
    ELSE
        DS=XDS
    ENDIF
    DO 160 I=1,3
        X2(I)=XL(I)
        Q(I)=QL(I)
        B2(I)=BL(I)
160 CONTINUE
    CALL INTGRT(X2,B2,BB2,S2,DEN2)
170 IF (BB2(N,1).GT.BMAX) GO TO 150
C
C    IF THE POINT IS LESS THAN BMAX MAKE SURE IT IS CLOSE ENOUGH. IF
C    NOT, TRY TO GET CLOSER
C
    CALL INTERP (BB2(N-2,1),S2(N-2),BMAX,SF,3)
    IF (ABS(SF-S2(N)).LT.SER) THEN
        CALL INTERP (BB2(N-2,1),RSV(N-2),BMAX,RS,3)
        IF (RS.LT.1.03) THEN
            NMANG=IA-1
            BMAXAN(IA)=-1
            GOTO 218
        ELSE
            GOTO 200
        ENDIF
    ENDIF

```

```

        ENDIF
    ENDIF
    DS=DS/2
    IF (ABS(SF) .GT. ABS(S2(N))) DS=CONI*(SF-S2(N))
    CALL INTGRT(X2,B2,BB2,S2,DEN2)
    GO TO 170
C
C    INTEGRAL IS COMPLETE USE STORED VALUES TO GET INVARIANT
200 CALL INVR(BMAX,BB2,S2)
    CALL INTERP(BB2(N-2,1),SXJ(N-2),BMAX,XXJ,3)
    CALL INTERP(BB2(N-2,1),DEN2(N-2),BMAX,XDN,3)
    N2LAST=N
    DO 205 I=1,3
        BLL2(I)=BL(I)
205 CONTINUE
C
C    ADD IN REMAINING CONTRIBUTION OF SECOND INVARIANT
215 XJ(IA)=XJ(IA)+ABS(XXJ)
    DENSTY(IA)=DENSTY(IA)+ABS(XDN)
C
216 CONTINUE
C
C
C    WE ARE DONE WITH ALL THE INTEGRALS - SET UP ANY ERROR VALUES
C
218 IF(NMANG.LT.NUMANG) THEN
    DO 219 I=NMANG+1,NUMANG
        XJ(I)=BMAXAN(NMANG+1)
        BMAXAN(I)=BMAXAN(NMANG+1)
        DENSTY(I)=BMAXAN(NMANG+1)
219 CONTINUE
    ENDIF
C
C    IF INVARIANT EXIST CALCULATE L'S
C
DO 220 I=1,NUMANG
    IF(BMAXAN(I) .GT. 0 .AND. BMAXAN(I) .NE. 100) THEN
        CALL HILTEL(BMAXAN(I),XJ(I),EL(I))
    ELSEIF(BMAXAN(I) .LT. 0) THEN
        EL(I)=-1
    ELSE
        EL(I)=100
    ENDIF
220 CONTINUE
    RETURN
END

```

```

SUBROUTINE CHECK(PANGLE,NUMANG,IER)
DIMENSION PANGLE(*)
C    CHECK TO SEE IF THE PITCH ANGLES ARE BETWEEN 0 AND 90 AND THE THE
C    PITCH ANGLE ARRAY IS MONOTONICALLY DECREASING
IER=0
IF (PANGLE(1).GT.90..OR.PANGLE(1).LE.0) IER=1
IF (NUMANG.GT.1) THEN
DO 10 I=2,NUMANG
IF (PANGLE(I).GT.PANGLE(I-1)) IER=1
IF (PANGLE(I).GT.90..OR.PANGLE(I).LE.0) IER=1
10  CONTINUE
ENDIF
RETURN
END

```

```

C      FUNCTION ADENS(X)
C
C      DETERMINE THE AVERAGE ATMOSPHERIC DENSITY AT A GIVEN ALTITUDE IN
C      GM/(CM2*Re)/3
C
C      DIMENSION X(3)
C      NOMINAL VALUE OF F10.7
C      DATA F107/114./
C      CONSTANT THAT CONVERTS TO CENTIMETERS AND APPLIES THE DIVIDE BY
C      THREE FROM GILL'S METHOD
C      5.7339E-3=6.371E8*2.7E-11/3
C      R=SQRT(X(1)**2+X(2)**2+X(3)**2)
C      IF (R.GT.3) THEN
C          ADENS=0
C      ELSE
C          A=0.99+.518*SQRT(F107/55)
C          R=(R-1)*6371
C          IF (R.LT.110) THEN
C              ADENS=0
C          ELSE
C              CON=(120-R)/(A*SQRT(R-103))
C              ADENS=5.7339E-3*EXP(CON)
C          ENDIF
C      ENDIF
C      RETURN
C      END

```

```

C      SUBROUTINE INVR(BMAX,BB,S)
C
C      PURPOSE
C      TO CALCULATE THE VALUE OF THE SECOND INVARIANT
C
C      METHOD
C      USE THE VALUES STORED IN THE S AND BB ARRAYS TO EVALUATE THE
C      INTEGRAL  $\sqrt{1-BB/BMAX}$  ALONG THE FIELD LINE. USE THE
C      SAME INTERGRATION METHOD (GILLS METHOD) USED IN INTEGRATING
C      THE FIELD LINE
C
C      INPUT -- COMMON BLOCK INTPAR
C      N      THE NUMBER OF INTEGRATION STEPS
C      BMAX   THE VALUE OF THE MAXIMUM MAGNETIC FIELD (THE POINT
C      WHERE THE PARTICLE HAS ITS MIRROR POINT)
C      BB     A REAL 2 DIMENSIONED ARRAY CONTAINING ALL OF THE
C      MAGNETIC FIELD MAGNITUDES CALCULATED IN THE FIELD LINE
C      INTEGRATION
C      S      AN ARRAY THAT HOLDS THE TOTAL INTEGRATED PATH LENGHT ALONG
C      FIELD LINE
C      OUTPUT -- COMMON BLOCK INTPAR
C      SXJ    THE VALUES OF THE SECOND INVARIANT INTEGRATION AT
C      EACH INTEGRATION STEP. SXJ(N) CONTAINS THE BEST
C      APPROXIMATION TO THE VALUE OF THE SECOND INVARIANT.
C      THE SAVING OF THE STEPS PERMITS THE USE OF INTERPOLATION
C      SCHEMES TO OBTAIN A MORE ACCURATE VALUE OF THE INVARIANT
C
C      CALLING SUBROUTINES
C      SUBROUTINE INVARM
C
C      CONSTANTS
C      P29    1.0-SQRT(.5)
C      OP7    1.0+SQRT(.5)
C
C      COMMON /INTPAR/DS,DEL,N,IERFLG,XL(3),XSV(100,3,4),
C      *RSV(100),RMIN(3),RMAG,IDSW,
C      *QL(3),Q(3),BL(3),SXJ(100),DDS
C      DIMENSION BB(100,4),S(100)
C
C      DIMENSION CON(4)
C      DATA (CON(I),I=1,4)/.5,.29289322,1.70710678,.5/
C      SXJ(2)=0.
C
C      START THE INTEGRATION LOOP.
C      THIS IS GILLS METHOD MADE SIMPLE IF ALL THE POINTS ARE GIVEN
C      CUMULATIVE ROUND OFF ERROR CONTROL IS NOT IMPLEMENTED
C      NN=N-1
C      DO 210 K=2,NN
C          TEMP1=0
C          DO 110 I=1,4
C              IF(BB(K,I).GE.BMAX) GO TO 110
C              ROOT=SQRT(1.-BB(K,I)/BMAX)
C              TEMP1=TEMP1+CON(I)*ROOT
C      110  CONTINUE
C          DELS=(S(K+1)-S(K))/3.
C          SXJ(K+1)=SXJ(K)+TEMP1*DELS
C      210  CONTINUE
C      RETURN
C      END

```

```

C      SUBROUTINE STEPSZ(X,B,BB)
C
C      PURPOSE
C      DETERMINE THE STEP SIZE FOR THE NEXT INTEGRATION STEP
C
C      METHOD
C      THE STEP SIZE OF THE RUNGE KUTTA INTEGRATION IS A FUNCTION
C      OF THE ERROR LIMITS, THE CURVATURE OF THE FIELD LINE, THE
C      GRADIENT IN THE MAGNETIC FIELD, AND THE ESTIMATED DISTANCE
C      TO THE END OF THE INTEGRATION.
C
C      INPUT -- COMMON BLOCK INTPAR
C      DEL      A PARAMETER SET UP BY THE CALLING PROGRAM TO SCALE THE
C      STEP SIZE. IT DEPENDS ON THE ERROR LIMITS OF THE
C      INTEGRATION.
C      B        A REAL ARRAY WHICH CONTAINS THE MAGNETIC FIELD VECTOR
C      AT THE CURRENT STEP
C      BL       A REAL ARRAY WHICH CONTAINS THE MAGNETIC FIELD VECTOR
C      AT THE PREVIOUS STEP
C      BB       A 2 DIMENSIONED REAL ARRAY
C      BB(N,1) IS THE MAGNETIC FIELD MAGNITUDE AT THE CURRENT
C      STEP
C      BB(N-1,1) IS THE MAGNETIC FIELD MAGNITUDE AT THE
C      PREVIOUS STEP
C      DDS      THE ESTIMATED STEP SIZE REQUIRED TO COMPLETE THE
C      INTEGRATION
C
C      INPUT/OUTPUT -- COMMON BLOCK INTPAR
C      DS       ON ENTRY TO THE ROUTINE DS CONTAINS THE SIZE OF THE
C      LAST STEP. THE ROUTINE RESETS THE VALUE TO THE BEST
C      STEP SIZE FOR THE NEXT INTEGRATION STEP.
C
C      CALLING SUBROUTINES
C      INVARM
C
C      TEMPORARY VARIABLES
C      CURVMN   THE MINIMUM ACCEPTABLE CURVATURE. THIS LIMITS THE STEP
C      SIZE IN THE VICINITY OF THE EARTH WHERE THE FIELD
C      CHANGES RAPIDLY
C      CURV     THE CURVATURE OF THE FIELD LINE
C
C      COMMON /INTPAR/DS,DEL,N,IERFLG,XL(3),XSV(100,3,4),
C      *RSV(100),RMIN(3),RMAG,IDSW,
C      *QL(3),Q(3),BL(3),SXJ(100),DDS
C      DIMENSION BB(100,4),BB2(100,4),B(3),B2(3),X(3),X2(3),S(3),S2(3)
C
C      DETERMINE THE MINIMUM CURVATURE
C
C      CURVMN=1.6667/(X(1)**2+X(2)**2+X(3)**2)**(.75)
C
C      DETERMINE THE CURVATURE OF THE FIELD BY USING THE RATE OF CHANGE
C      OF THE UNIT FIELD VECTOR OVER THE LAST STEP
C
C      CURV=0.
C      DO 50 I=1,3
C      CURV=CURV+((B(I)/BB(N,1)-BL(I)/BB(N-1,1))/DS)**2
50  CONTINUE
C      CURV=SQRT(CURV)
C      CURV=AMAX1(CURV,CURVMN)
C
C      SET UP THE NEW STEP SIZE AND LIMIT THE STEP SIZE TO LESS THAN 2.8
C      EARTH RADIUS TO PREVENT THE INTEGRATION FROM STEPPING OUT OF THE
C      VALID FIELD REGION

```

```

C      DS=DEL/CURV
      DS=SIGN(AMIN1(ABS(DS),1.0),DS)
      IF(N.LE.3) DS=DS*(N*2-3)*.2
C
C      IF THE DISTANCE TO THE END OF THE INTEGRATION IS SMALLER THAN THE
C      NEW STEP SIZE, SET THE STEP SIZE TO THE SMALLER VALUE.
C
      IF(ABS(DDS).LT.ABS(DS)) DS=DDS
      RETURN
      END

```

SUBROUTINE INTGRT(X,B,BB,S,DEN)

PURPOSE

THIS SUB MODULE PERFORMS A SINGLE RUNGE-KUTTA INTEGRATION  
STEP AND UPDATES ALL OF THE VARIABLES IN THE INTEGRATION LOOP

METHOD

PERFORM A SINGLE FOURTH ORDER INTEGRATION STEP USING GILLS  
METHOD OF INTEGRATION (REF. S. GILL CAMBRIDGE PHILOSOPHICAL  
SOCIETY PROCEEDINGS VOL. 47, 1951)

INPUT -- COMMON BLOCK INTPAR

DS THE INTEGRATION STEP SIZE IN UNITS OF EARTH RADII.  
THE INTEGRATION MOVES THE SPACE COORDINATE A DISTANCE  
DS ALONG THE MAGNETIC FIELD LINE. IF DS IS POSITIVE,  
MOTION IS IN THE DIRECTION OF THE FIELD. IF DS IS  
NEGATIVE MOTION IS ANTI-PARALLEL TO THE FIELD.

INPUT/OUTPUT -- COMMON BLOCK INTPAR

N THE INTEGRATION STEP NUMBER. IT IS INCREMENTED BY  
ONE AT THE END OF THIS ROUTINE. (NOTE N=2 IS THE  
BEGINNING OF THE INTEGRATION)  
X A REAL ARRAY GIVING THE VECTOR LOCATION OF THE  
INTEGRATION VARIABLE.  
INPUT - THE INITIAL POSITION PRIOR TO THE INTEGRATION  
STEP  
OUTPUT- THE FINAL VALUE AFTER THE INTEGRATION STEP  
B A REAL ARRAY CONTAINING THE VECTOR MAGNETIC FIELD  
IN GAUSS  
INPUT - THE VECTOR FIELD BEFORE THE INTEGRATION STEP  
OUTPUT- THE VECTOR FIELD AFTER THE STEP  
Q A REAL ARRAY CONTAINING AN ERROR CONTROL VARIABLE  
USED BY GILLS INTEGRATION METHOD  
INPUT - ERROR FROM PREVIOUS STEP  
OUTPUT- ERROR AFTER PRESENT STEP FOR INPUT TO SUBSEQUENT  
STEPS

OUTPUT -- COMMON BLOCK INTPAR

S A REAL ARRAY WHICH SAVES EACH OF THE DISTANCES (SINCE  
THE START OF THE INTEGRATION) ALONG THE MAGNETIC FIELD  
LINE.  
S(2)=0  
S(N+1)=S(N)+DS ETC.  
XSV A REAL 3 DIMENSIONED ARRAY WHICH SAVES THE VECTOR  
POSITION IN EARTH RADII FOR EACH OF THE INTEGRATION  
STEPS. XSV(N,1,1), XSV(N,2,1), XSV(N,3,1) ARE VECTOR  
CARTESIAN POSITION COORDINATES CORRESPONDING TO POSITION  
S(N) ON THE FIELD LINE  
BB A REAL 2 DIMENSIONED ARRAY WHICH SAVES THE MAGNITUDE  
OF THE MAGNETIC FIELD FROM EACH INTEGRATION STEP.  
BB(N,1) IS MAGNETIC FIELD VALUE AT DISTANCE S(N).  
BB(N-1,2), BB(N-1,3), BB(N-1,4) ARE THE INTERMEDIATE  
VALUES OF THE FIELD USED BY GILLS METHOD TO GET FROM  
BB(N-1,1) TO BB(N,1).  
XL A REAL ARRAY WHICH SAVES THE INITIAL POSITION VALUES  
PRIOR TO STARTING THE INTEGRATION STEP  
BL A REAL ARRAY WHICH SAVES THE VECTOR MAGNETIC FIELD  
VALUES PRIOR TO STARTING THE INTEGRATION STEP  
QL A REAL ARRAY WHICH SAVES THE INITIAL VALUES OF THE  
ERROR CONTROL VARIABLE  
IERFLG AN ERROR CONTROL INDICATOR WHICH IS USED BY THE CALLING  
PROGRAM TO CONTROL THE PROGRAM FLOW  
IERFLG = 0 NO ERROR  
IERFLG = 1 INTEGRATION IS OUTSIDE VALID FIELD LIMITS

```

C                                     OR THE MAXIMUM STEP NUMBER (100) HAS BEEN
C                                     REACHED.
C
C   CONSTANTS
C       P29      1.0-SQRT(0.5)
C       OP7      1.0+SQRT(0.5)
C
C   VARIABLES
C       P5DS     .5 * STEP SIZE
C       P29DS    (1.0-SQRT(0.5)) * STEP SIZE
C       OP7DS    (1.0-SQRT(0.5)) * STEP SIZE
C       RR,SS    REAL ARRAYS USED BY GILLS METHOD TO MINIMIZE COMPUTER
C               TIME AND MINIMIZE ROUND OFF ERROR
C
C   CALLING SUBROUTINES
C       SUBROUTINE INVARM
C
C   SUBROUTINES REQUIRED
C       SUBROUTINE BMNEXT
C       COMMON/BXYZCM/YEAR, DAYYR, UT, KODE, JSW
C
C   COMMON /INTPAR/DS, DEL, N, IERFLG, XL(3), XSV(100,3,4),
C   *RSV(100), RMIN(3), RMAG, IDSW,
C   *QL(3), Q(3), BL(3), SXJ(100), DDS
C   DIMENSION BB(100,4), B(3), X(3), S(100), DEN(100)
C   DIMENSION SS(3), RR(3)
C   DATA P29, OP7/.29289322, 1.70710678/
C   IERFLG=0
C   SAVE THE INITIAL VALUES.  THESE INITIAL VALUES MAY BE NEEDED IF
C   IF THE INTEGRATION STEP IS UNSUCCESSFUL (GOES TOO FAR) AND THE
C   STEP MUST BE REPEATED.
C
C   DO 65 I=1,3
C       XL(I)=X(I)
C       QL(I)=Q(I)
C       BL(I)=B(I)
C   65  CONTINUE
C
C   SET UP THE CONSTANST NEEDED BY THE INTEGRATION LOOP
C
C       P5DS=.5*DS
C       P29DS=P29*DS
C       OP7DS=OP7*DS
C
C   BEGIN GILLS METHOD (GILL 1951) OF FOURTH ORDER INTEGRATION
C
C       TEMP2=P5DS*ADENS(X)
C       DO 70 I=1,3
C           SS(I)=P5DS*R(I)/BB(N,1)
C           RR(I)=SS(I)-Q(I)
C           X(I)=X(I)+RR(I)
C           Q(I)=Q(I)+3.*RR(I)-SS(I)
C           XSV(N,I,2)=X(I)
C   70  CONTINUE
C       TEMP2=TEMP2+P29DS*ADENS(X)
C       CALL BMNEXT(X,R, BB(N,2))
C       DO 71 I=1,3
C           SS(I)=P29DS*B(I)/BB(N,2)
C           RR(I)=SS(I)-P29*Q(I)
C           X(I)=X(I)+RR(I)
C           Q(I)=Q(I)+3.*RR(I)-SS(I)
C           XSV(N,I,3)=X(I)
C   71  CONTINUE
C       TEMP2=TEMP2+OP7DS*ADENS(X)

```

```

      CALL BMNEXT(X,B,BB(N,3))
      DO 72 I=1,3
      SS(I)=OP7DS*B(I)/BB(N,3)
      RR(I)=SS(I)-OP7*Q(I)
      X(I)=X(I)+RR(I)
      Q(I)=Q(I)+3.*RR(I)-SS(I)
      XSV(N,I,4)=X(I)
72    CONTINUE
      TEMP2=TEMP2+P5DS*ADENS(X)
      CALL BMNEXT(X,B,BB(N,4))
      DO 73 I=1,3
      SS(I)=P5DS*B(I)/BB(N,4)
      RR(I)=(SS(I)-Q(I))/3.
      X(I)=X(I)+RR(I)
      Q(I)=Q(I)+3.*RR(I)-SS(I)
      XSV(N+1,I,1)=X(I)
73    CONTINUE
      N=N+1
C
C      SAVE THE CURRENT DISTANCE ALONG THE FIELD LINE
C
      S(N)=S(N-1)+DS
      DEN(N)=DEN(N-1)+TEMP2
C
C      OBTAIN THE CURRENT VALUES OF THE MAGNETIC FIELD
C
      CALL BMNEXT(X,B,BB(N,1))
C
C      IF N IS TOO BIG, SET ERROR FLAG
C      IF(N.GE.100) IERFLG=1
C
C      IF OUTSIDE INTEGRATION LIMITS SET ERROR FLAG
C      R=X(1)**2+X(2)**2+X(3)**2
C      RSV(N)=SQRT(R)
C      IF EXTERNAL FIELD IS USED STAY WITHIN VALID REGION
C      IF((R.GT.144..OR.BB(N,1).LT.0.00015).AND.JSW.GE.0) IERFLG=1
C      IF BELOW EARTHS SURFACE SET FLAG NEGATIVE
C      IF(RSV(N).LT.1.03) IERFLG=-1
      RETURN
      END

```

SUBROUTINE INTERP (BB,CC,D,E,J)

PURPOSE  
INTERPOLATION ROUTINE

METHOD

GIVEN A SET OF THREE X,Y POINT PAIRS, INTERP FINDS THE SOLUTION  
TO THE THREE LINEAR EQUATIONS EXPRESSING THE LOGARITHM OF THE  
DEPENDENT VARIABLE Y AS A SECOND ORDER POLYNOMIAL OF THE  
INDEPENDENT VARIABLE X. ( $\log Y = A \cdot X^2 + B \cdot X + C$ )  
USING THE BINOMIAL FORMULA, X CAN THEN BE EVALUATED AT A  
SPECIFIED VALUE OF Y1  
$$X = (-B \pm \sqrt{B^2 - 4 \cdot A \cdot (C - \log(Y1))}) / (2 \cdot A)$$

INPUT -- ARGUMENT LIST

BB A REAL ARRAY CONTAINING THE THREE VALUES OF THE  
DEPENDENT VARIABLE  
CC A REAL ARRAY CONTAINING THE THREE CORRESPONDING VALUES  
OF THE INDEPENDENT VARIABLE  
J A FLOW CONTROL VARIABLE  
IF J IS LESS THAN 0  
FIT THE POLYNOMIAL TO CC AND BB AND FIND THE MINIMUM  
VALUE OF THE DEPENDENT VARIABLE  
IF J IS GREATER THAN 0  
USE THE BINOMIAL FORMULA TO FIND THE VALUE OF  
THE INDEPENDENT VARIABLE WHEN THE DEPENDENT VARIABLE  
HAS THE VALUE D. CHOOSE THE ROOT THAT IS CLOSEST TO CC(J)  
D WHEN J IS GREATER THAN ZERO, D IS USED FOR INPUT.  
IT IS THE VALUE OF THE DEPENDENT VARIABLE WHERE THE  
SOLUTION TO THE DEPENDENT VARIABLE IS WANTED

OUTPUT -- ARGUMENT LIST

D WHEN J IS LESS THAN 0, D OUTPUTS THE VALUE OF THE  
DEPENDENT VARIABLE WHERE THE FUNCTION IS A MINIMUM  
E WHEN J IS LESS THAN 0, E OUTPUTS THE VALUE OF THE  
INDEPENDENT VARIABLE WHERE THE FUNCTION IS A MINIMUM  
WHEN J IS GREATER THAN 0, E OUTPUTS THE VALUE OF THE  
INDEPENDENT VARIABLE WHERE THE FUNCTION HAS THE VALUE D

CALLING SUBROUTINES  
SUBROUTINE INVARM

VARIABLES

X2,X3,Y1,Y2,Y3,DD ARE USED BY THE LINEAR EQUATION SOLUTION  
TO MINIMIZE COMPUTER TIME  
A,B,C THE THREE POLYNOMIAL COEFFICIENTS  
DIS  $B^2 - 4 \cdot A \cdot C$   
SA,SB THE TWO ROOTS OF THE POLYNOMIAL

DIMENSION BB(3),CC(3)  
REAL\*8 Y1,Y2,Y3,X2,X3,DD,A,B,C,DIS

SET UP THE INITIAL VARIABLES, MOVE THE ORIGIN OF THE INDEPENDENT  
VARIABLE TO CC(1)

Y1=ALOG(BB(1))  
Y2=ALOG(BB(2))  
Y3=ALOG(BB(3))  
X2=CC(2)-CC(1)  
X3=CC(3)-CC(1)

SOLVE THE LINEAR EQUATIONS  
DD=(X3-X2)\*X2\*X3  
IF(DD.EQ.0) THEN

```

      IF (J.LT.0) THEN
        D=BB(2)
      ELSE
        E=CC(J)
      ENDIF
      RETURN
    ENDIF
    A=(X3*(Y1-Y2)+X2*(Y3-Y1))/DD
    B=(X3**2*(Y2-Y1)-X2**2*(Y3-Y1))/DD
C
C   IF J THE FLOW CONTROL VARIABLE IS LESS THAN ZERO BRANCH TO
C   MINIMUM EVALUATION ROUTINE
    IF (J.LT.0) GO TO 100
    C=Y1-DLOG(D)
    DIS=B**2-4.*A*C
C
C   IF DIS IS NEGATIVE NO SOLUTION EXIST, EXCHANGE DEPENDENT AND
C   INDEPENDENT VARIABLE ROLES AND TRY ANOTHER SOLUTION
    IF (DIS.LE.0.) GO TO 200
    DIS=DSQRT(DIS)
C
C   OBTAIN THE TWO ROOTS
    SA=(-B+DIS)/(2.*A)+CC(1)
    SB=(-B-DIS)/(2.*A)+CC(1)
    E=SA
C
C   FIND THE ROOT CLOSEST TO CC(J)
    IF (ABS(SB-CC(J)).LT.ABS(SA-CC(J))) E=SB
    RETURN
C
C   FIND THE VALUES AT THE MINIMUM
100  X=-B/(2.*A)
      E=X+CC(1)
      XM=A*X**2+B*X+Y1
      D=EXP(XM)
      RETURN
C
C   ALTERNATE INTERPOLATION SCHEME PLACED HERE AS A SAFEGUARD
C   AGAINST A STRANGE FIELD CONFIGURATION CAUSING AN IMAGINARY
C   SOLUTION (EXCHANGE THE ROLES OF DEPENDENT AND INDEPENDENT
C   VARIABLES)
200  Y1=CC(1)
      Y2=CC(2)
      Y3=CC(3)
      X2=BB(2)-BB(1)
      X3=BB(3)-BB(1)
      DD=(X3-X2)*X2*X3
      IF (DD.EQ.0) THEN
        E=CC(J)
        RETURN
      ENDIF
      A=(X3*(Y1-Y2)+X2*(Y3-Y1))/DD
      B=(X3**2*(Y2-Y1)-X2**2*(Y3-Y1))/DD
      DX=D-BB(1)
      E=(A*DX+B)*Dx+Y1
      RETURN
    END

```

SUBROUTINE MGLONG(X,S,SF,XMLONG,RMIN,RMAG)

PURPOSE

TO DETERMINE THE MAGNETIC LONGITUDE OF THE MINIMUM B LOCATION  
OF THE MAGNETIC FIELD LINE

METHOD

GIVEN A LOCUS OF POSITIONS ALONG A FIELD LINE AS A FUNCTION  
OF THE SCALAR DISTANCE ALONG THE FIELD LINE AND GIVEN THE  
SCALAR DISTANCE WHERE THE FIELD IS A MINIMUM, THE ROUTINE  
FINDS THE VECTOR POSITION OF THE MINIMUM. IT THEN TRANSFORMS  
THIS MINIMUM TO OFFSET DIPOLE COORDINATES AND CALCULATES  
THE MAGNETIC LONGITUDE OF THE MINIMUM

NOTE\*\*\*\*\*THE CONSTANT ISWTCH IS SET BY A DATA STATEMENT,  
IF IT IS SET TO ZERO XMLONG IS CALCULATED USING A CENTERED  
DIPOLE COORDINATE SYSTEM WITH ZERO LONGITUDE AT 69 DEGREES  
WEST GEOGRAPHIC. IF ISWTCH IS SET NON-ZERO, AN OFFSET DIPOLE  
COORDINATE SYSTEM IS USED WITH XMLONG=0 GOING THROUGH  
GREENWHICH

INPUT -- ARGUMENT LIST

X A REAL 2 DIMENSIONED ARRAY CONTAINING THE LOCUS OF  
POINTS ALONG A FIELD LINE  
X(1,1), X(1,2) AND X(1,3) ARE THE X, Y, Z VALUES  
(RIGHT HANDED CARTESIAN COORDINATES) AT THE FIRST  
POINT, X(2,1), X(2,2) AND X(2,3) THE SECOND LOCATION  
AND X(3,1), X(3,2) AND X(3,3) ARE AT THE THIRD LOCATION  
THE FIRST DIMENSION OF X MUST BE THE SAME AS THE  
CALLING PROGRAMS DIMENSION - IN THIS CASE IT IS 100  
S A REAL ARRAY CONTAINING THE SCALAR DISTANCE ALONG THE  
FIELD LINE IN EARTH RADII. S(1) IS THE SCALAR DISTANCE  
TO THE X(1,1), X(1,2), X(1,3) POINT FROM THE START  
OF THE INTEGRATION, S(2) IS THE DISTANCE TO X(2,1), ...  
SF THE SCALAR DISTANCE TO THE MAGNETIC MINIMUM

OUTPUT -- ARGUMENT LIST

XMLONG THE MAGNETIC LONGITUDE (IN DEGREES) OF THE MINIMUM  
OF THE MAGNETIC LINE OF FORCE  
IF ISWTCH IS ZERO, THE ZERO OF MAGNETIC LONGITUDE IS  
ALONG 69 DEG WEST GEOGRAPHIC  
IF ISWTCH IS NOT ZERO, THE ZERO OF MAGNETIC LONGITUDE  
IS THROUGH GREENWHICH

CONSTANTS

DX THE 3 VECTOR COMPONENTS OF THE LOCATION OF THE OFFSET  
DIPOLE IN EARTH RADII (GEOGRAPHIC CARTESIAN COORDS)  
A22-A34 TRANSFORMATION MATRIX TO OFFSET DIPOLE COORDS. FIRST  
ROTATE ABOUT THE GEOGRAPHIC Z AXIS, TO THE MERIDIAN  
CONTAINING THE OFFSET DIPOLE, THEN ABOUT THE NEW Y AXIS  
TO THE LATITUDE CONTAINING THE OFFSET DIPOLE AND THEN  
ABOUT THE NEW Z AXIS SUCH THAT THE ZERO OF LONGITUDE  
PASSES THROUGH GREENWHICH  
ISWTCH A FLOW CONTROL CONSTANT  
IF SET TO ZERO BY THE DATA STATEMENT USE CENTERED DIPOLE  
COORDINATES  
IF SET NON-ZERO USE OFFSET DIPOLE COORDINATES  
SIN D SINE OF THE COLATITUDE OF THE CENTERED DIPOLE AXIS  
COS D COSINE OF THE COLATITUDE OF THE CENTERED DIPOLE AXIS  
S69 SINE OF 69 DEGREES  
C69 COSINE OF 69 DEGREES

TEMPORARY VARIABLES

XF,X1,X2,Y1,Y2,Y3,A,B,DD THESE VARIABLE ARE USED IN THE  
INTERPOLATION LOOP TO MINIMIZE THE NUMBER OF MEMORY

```

C          REFERENCES AND TO MINIMIZE THE NUMBER OF MULTIPIES
C          XT      A REAL ARRAY HOLDING THE LOCATION OF THE MINIMUM AND
C          LATER THE OFFSET MINIMUM OF THE FIELD LINE
C          XP,YP   THE POSITION OF THE MINIMUM IN OFFSET MAGNETIC CORDS.
          DIMENSION X(100,3),S(100),DX(3),XT(3),RMIN(3)
          DATA DX(1),DX(2),DX(3)/0.0576,-0.0321,-0.0184/
          DATA A22,A23,A24,A32,A33,A34/0.97056,0.23948,-0.02556,
          *-0.22969,0.95232,0.20082/
          DATA SIND,COSD,S69,C69/.2027872954,.9792228106,.9335804265,
          *.3583679495/

C
C
C          *****SET UP THE FLOW CONTROL SWITCH*****
C          COORDINATE SYSTEM DEFINITION USED. (SEE METHOD)
C          DATA ISWTCH/1/

C          BEGIN QUADRATIC INTERPOLATION
          XF=SF-S(1)
          X2=S(2)-S(1)
          X3=S(3)-S(1)
          DD=(X3-X2)*X2*X3

C
C          INTERPOLATE EACH COMPONENT SEPERATELY
          DO 10 I=1,3
            Y1=X(1,I)
            Y2=X(2,I)
            Y3=X(3,I)
            A=(X3*(Y1-Y2)+X2*(Y3-Y1))/DD
            B=(X3**2*(Y2-Y1)-X2**2*(Y3-Y1))/DD

C
C          EVALUATE THE POSITION OF THE MINIMUM
          XT(I)=(A*XF+B)*XF+Y1
          RMIN(I)=XT(I)
10      CONTINUE
          RMAG2=XT(1)**2+XT(2)**2+XT(3)**2
          RMAG=SQRT(RMAG2)

C
C          IF ISWTCH IS ZERO GO TO CENTERED DIPOLE DEFINITION
          IF (ISWTCH.EQ.0) GO TO 30

C          ADD IN THE DIPOLE OFFSET
          DO 20 I=1,3
20      XT(I)=XT(I)+DX(I)

C
C          TRANSFORM TO OFFSET DIPOLE COORDINATES AND EVALUATE THE LONGITUDE
          XP=A22*XT(1)+A23*XT(2)+A24*XT(3)
          YP=A32*XT(1)+A33*XT(2)+A34*XT(3)
          GO TO 40

C
C          TRANSFORM TO CENTERED DIPOLE COORDINATES
30      XP=(XT(1)*C69-XT(2)*S69)*COSD-XT(3)*SIND
          YP=XT(1)*S69+XT(2)*C69

C
C          CALCULATE MAGNETIC LONGITUDE
40      XMLONG=ATAN2(YP,XP)*57.2957795
          IF(XMLONG.LT.0.) XMLONG=XMLONG+360.
          RETURN
          END

```

```

SUBROUTINE HILTEL (B,XI,VL)
C
C PURPOSE
C   CALCULATE THE L VALUE
C   THE ORIGINAL MCILWAIN L EXPANSION GIVEN BY THE OLD
C   SUBROUTINE CARMEL HAS BEEN REPLACED BY HILTONS SIMPLER
C   EXPANSION. DIFFERENCES BETWEEN HILTONS AND MCILWAINS
C   EXPANSION ARE TYPICALLY LESS THAN .01 PERCENT.
C
C METHOD
C   SEE J. HILTON, J. GEOPHYS. RES. 76, 6952 (1971)
C
C INPUT -- CALLING SEQUENCE
C   B   THE MAGNETIC FIELD AT THE PARTICLE MIRROR POINT
C   XI  THE SECOND INVARIANT EVALUATED BETWEEN MIRROR POINTS
C       EXPRESSED IN UNITS OF EARTH RADII
C
C OUTPUT -- CALLING SEQUENCE
C   VL  THE L VALUE
C
C THE NEXT STATEMENT CONTAINS THE ORIGINAL MCILWAIN MOMENT
C DATA XM/.311653/
C USE THE DIPOLE MOMENT CALCULATED FROM THE CURRENT FIELD MODEL
COMMON /MOMENT/XM
IF(XI.GT.1.0E-36) GO TO 10
VL=(XM/B)**(1./3.)
RETURN
10 X=XI*(B/XM)**(1./3.)
V=1.+X*(1.35047+X*(.465376+.0475455*X))
VL=(V*XM/B)**(1./3.)
C END COMPUTE L
RETURN
END

```